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INTEGRATED FUNDAMENTAL RESEARCH ON CURRENT COLLECTION

Doris Kuhlmann-Wilsdorf
School of Engineering and Applied Science
University of Virginia
Thornton Hall
Charlottesville, VA 22903

Leo Tran
Project Engineer
ARDEC

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Doris Kuhlmann-Wilsdorf, School of Engineering and Applied Science
Leo Tran, ARDEC, Project Engineer

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School of Engineering and Applied Science
University of Virginia
Thornton Hall
Charlottesville, VA 22903

ARDEC, FSAC
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13. ABSTRACT (Maximum 200 words)

The aim of our research was to add to the basic understanding in the area of current collection with particular emphasis on topics likely to benefit practical objectives. Under sponsorship of this contract, 23 papers were published in the international literature. Additionally, 13 invited lectures and 11 contributed lectures on various aspects of this research were delivered at universities, research laboratories, and international conferences by the principal investigator and coworkers. The development of a novel metal fiber material for sliding electrical contacts was continued with much success. This is expected to become very useful for making metal fiber brushed for homopolar motors/generators, as well as, for EML armatures. By any objective measure, the results of this program have been valuable.

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INTRODUCTION

The aim of our research has been to add to basic understanding in the area of current collection with particular emphasis on topics likely to benefit practical objectives. These were 1. Studies on the be-havior of adsorbed moisture on sliding interfaces. 2. Investigation of the role of adsorbed moisture in graphite lubrication. 3. Studies on the sub-surface deformation of materials at sliding interfaces. 4. Development of a system for the automatic testing of electrical brushes. 5. Development of a new metal fiber material for sliding electrical contacts. All of the results obtained advance our knowledge of electrical contacts, and some are very useful for the design and operation of electric contacts, especially metal fiber brushes and EML armatures, as pointed out in the respective sections "Practical Significance".

PRINCIPAL RESEARCH TOPICS AND RESULTS

Studies on the Behavior of Adsorbed Moisture on Sliding Interfaces (Refs. 1 through 8)

From research in our own laboratory[1] it had been known for more than 15 years that under "clean" conditions in the atmosphere, there are two monolayers of water between the contact spots of sliding metals. The importance of these layers for inhibiting cold-welding and thereby disastrous wear rates had been clearly recognized throughout, as also the fact that those two monolayers of water provide the theoretically lowest possible film resistivity for sliding contacts, namely $\sigma \approx 10^{-12}\Omega.m^2$. It had therefore been clear for many years past that the maintenance of those two monolayers of adsorbed water are critical for the good performance of unlubricated sliding metal contacts. However, seeing that the thickness of adsorbed moisture on free surfaces varies widely with humidity, it was mysterious how the discussed two monolayers could be present so reliably, provided only that adequate moisture levels were maintained in the ambient atmosphere and that chemical attack, e.g. of oxygen on copper, was avoided.

The research of these past three years has answered that question: Confined between macroscopically contacting solid surfaces, thick adsorbed fluid films are squeezed out under pressure. Following ordinary draining, with increasing pressure the films order into parallel layers once their thickness is reduced below several nanometers. From then on, with increasing pressure the fluid layers are squeezed out step-wise, with the requisite pressure increments for reducing the number of layers rising. At moderate pressures only two layers remain but the expulsion of those last two molecular layers requires pressures much higher than prevail at typical contact spots, i.e. comparable to the hardness of the softer of the two contacting materials. The condition of a contact spot is then as depicted in figure 1 of ref.2.

The above facts are presented in refs. 2 - 8 which discuss numerous related effects of adsorbed moisture on the behavior of sliding contacts. Specifically examined were, among others: 1. The contribution to sliding friction made by the adsorbed moisture layers as a function of load and sliding speed; 2. the small, gradual increase of the film thickness at contact spots with sliding

speed which yet results in a significant increase of the film resistivity σ and thus the contact resistance and 3. stick-slip, which is a quite frequent by-product of those layers.

The pertinent measurements were made in the hoop apparatus of which a diagram may be seen in figure 2. It consists of a vertical hoop (H), i.e. a short piece of hollow tubing, rotating on horizontal rollers (R). The sample (S) slides in a circumferential shallow track (T) cut into the hoop. Through the hoop rotation the sample is carried upwards on an increasing slope until it slides back down at a critical inclination, driven by gravity. The sample position, and hence the momentary slope, is determined from the attendant rotation via a piece of polaroid material (P) mounted on top of the sample. The angle of the polaroid material is monitored through the intensity variation of a light beam (LB) passing through it on its way from a light source (L) and an analyzer to a photosensitive diode (D). The applied load at the interface between sample and hoop track is applied through disk-shaped weights (W) with cylindrical holes which are slipped over horizontal rods attached to the sample holder. They rods are carefully positioned such that the center of gravity of the sample assembly and including whatever weights may be applied lies very close to the interface. If this were not done, the sample assembly could either topple over, if the center of gravity were too high, or would execute oscillations which would severely interfere with the measurements.

The samples were mostly metal fiber brushes made of thousands of 50μm thick gold-plated copper fibers sliding in a humidified but otherwise inert atmosphere on a gold-plated track. These conditions were chosen so as to study the effects of the adsorbed moisture film on elastic contact spots, without interference by complications due to chemical attack and constriction resistance. By way of explanation: When in metal-metal sliding the number of contact spots is made very large and the normal force per contact spot very small, as in our samples, the average pressure on the spots falls below the hardness of the softer of the two metals. If so, the spots remain elastic instead of being plastically deformed as in the overwhelming majority of all metal-metal sliding systems. However, the plastic deformation at the contact spots, in fact in the sub-surface region on the softer side, tends to control the coefficient of friction and therefore makes the study of the behavior of the adsorbed moisture via its contribution to friction impossible with plastic contact spots.

Depending on conditions, the samples executed harmonic oscillations, stick-slip motions or irregular/smooth sliding. Examples of these types of motion are seen in Figure 3 of ref.7 which illustrates how they depend on humidity between 20% and 90% and sliding velocities between 0.05cm/sec and 2.8cm/sec, under 0.5N = 50gwt load in nitrogen at ambient pressure and temperature. Note the tendency for smooth sliding at low humidity and high load, the tendency for harmonic oscillations at high speeds and high humidity, and pronounced stick-slip at high humidity and low speeds. A similar set of curves obtained for a much higher load showed a slow dependence on load (and thus contact spot size since the number of contact spots is in essence fixed by the number of fibers in the sample).

Very large numbers of such curves and correlated contact resistances were recorded automatically in digitized form. The essential conclusions drawn from these are as already stated,

namely that a double molecular layer of water separates the two sides at contact spots with an accumulation of water pushed ahead and a depleted zone gradually filled-in behind contact spots as indicated in figure 1. After the outlines of the model of figure 1 were established, the careful analysis of additional data was used to infer the dependence of the three major contributions to friction on relative humidity and sliding speed. In line with the model of figure 1, these major contributions are friction between the two layers at the interface, viscous flow of the displaced moisture about the contact spots, and increased contact spot area through the pseudo-pressure exerted by menisci. In addition, increasing speed causes excess water molecules, beyond the two monolayers, to be trapped at the contact spots. That excess lowers friction directly at the interface. Correspondingly, the gradual draining of that excess increases friction during rest periods.

Some major results are shown in Figs.3 to 6 from ref.8. Specifically, stick-slip indicates decrease of friction with speed at small velocities, smooth sliding indicates increasing friction with speed, and oscillations indicates speed-independence of friction. All three conditions can be realized, depending on speed and humidity as seen in figure 3. This wide variety is due to the complex relationships between the different contributions made to friction in accordance with figure 1. These include friction between the double layer of molecules, viscous flow about the spots, effects of meniscus formation and excess molecules trapped, or "buried", between the double layers. Menisci tend to increase friction, in fact depending on contact spot size, partly through the accumulation of extra moisture about the spots and partly through the effective extra pressure exerted by their surface tension. By contrast, "buried" molecules tend to lower friction much like sand on a road, and their concentration rises with speed in an effect reminiscent of hydroplaning. During rest periods, excess molecules drain out. The speed of such draining rises with decreasing contact spot size and with increasing local pressure. Also meniscus form-ation depends on time and contact spot size. It takes place during rest periods by the attraction of adsorbed moisture from the vicinity of the contact spots and motion destroys menisci.

Add to these complexities the effect of "shear thinning"to which we shall return presently, and all our data, including many more not specifically presented in this report but found in the cited publications, can be explained. In fact the progress of the research was the reverse, of course, in that a great mass of data, including typically resistance measurements taken simultaneously with friction data, were analyzed and parameters were varied purposefully to check out developing hypotheses before the theory summarized above was completed.

Specifically regarding the data in figure 3, the slow draining of excess buried molecules which increases friction during rest periods, is the key for understanding the dependence of stick-slip on sliding speed as well as on humidity. The requisite rest periods for lowering friction via draining of excess molecules decreases with sliding speed. Therefore stick-slip becomes less pronounced and ultimately ceases with increasing average sliding speed. However, with decreasing humidity, adsorbed layers outside of spots become thinner and the discussed trapping of excess molecules at the interface decreases until such trapping and therewith stick-slip ceases.

For appreciating the influence of other components of the model besides draining of "buried" molecules, turn to figure 6, showing the dependence of the friction coefficient (μ) on speed (v). The expected linear increase of μ with v, in accordance with Newtonian behavior of the fluid flow in the flow pattern of figure 1 at right, can be seen at slow speeds.

The decrease of μ beyond the maximum at about 2 cm/sec was an unexpected surprise. After due consideration of all aspects of the measurements it has been explained by viscosity reduction through "shear thinning". That effect occurs through the alignment of the molecules along flow lines at high shear rates. This is very familiar for chain molecules but it is also expected for water on the basis of this writer's earlier theory of melting[9,10]. If this interpretation is correct, as we believe it to be, not only does the fluid film behave much like an ordinary fluid, but the "shear thinning" effect is otherwise experimentally undocumented for water. The reason that we may see it here is that the required shear rates in the cases of simple liquids are very high indeed, which they are about the very small contact spots in our samples, e.g. at 1cm/sec sample speed in the order 10^4/sec.

The overall dependence of friction on humidity is also more complicated than the expected monotonic rise with humidity due to increasing thickness of the adsorbed fluid film. Instead, as seen in Figs.3 and 4, initially the friction decreases with humidity, accompanied by a rise of contact resistance. This combination of observations indicates a minor increase of film thickness due to excess "buried molecules" beyond the two monolayers that are in equilibrium at rest, which are trapped through increasing speed as already mentioned, and that their presence decreases friction, acting much like sand or gravel on a road. Lastly, a full interpre-tation of all of the results requires one further effect, namely the capillary action of the meniscus which forms about each contact spot except at quite low humidities. In fact, the surface tension and local curvature at the menisci cause an extra pressure, as if the load per contact spot were increased. Including all of the outlined effects, all of the data can be explained.

One may be skeptical how reliable a theoretical model of such relative complexity can be. However, it is clear that with the possible exception of shear thinning all of the discussed effects, i.e. 1. Newtonian flow about the contact spots, 2. squeezing out of excess moisture between the spots, 3. trapping of excess molecules with increasing speed and thus increase of the remnant film thickness between the spots with increasing relative velocity, 4. increase of film thickness with increasing spot size at same pressure, 5. formation of menisci and the excess pressure caused by them, must be there physically. Correspondingly, any model not taking those effects into consideration cannot be very realistic, and our model has been vindicated by the fact that it is in harmony with all of the very complex data and relationships. This is ever more convincing because the data are still considerably more extensive than presented in Figs.2 to 6, including additionally very detailed hysteresis loops of friction versus speed within any one stick-slip cycle and, above all, correlated contact resistance measurements for all experiments. The observational basis for the model is thus altogether much more complex and extensive than can be discussed in this final report, and the reader is referred to the cited publications. Therefore we are very pleased with the ground covered and the insights gained, having confidence that the model as it now stands is reliable.

Practical Significance *- Adsorbed moisture is about us all the time, on virtually every surface we see, touch or use at ambient temperature. Except under stringent precautions or relatively high work-ing temperatures, moisture films will therefore be present on all surfaces. As we may now deduce from the discussed research, those unseen but ubiquitous moisture films are enormously important not only for electrical contacts but in our daily lives. Evidently, they are largely responsible for the remarkable fact that in our surroundings, firstly untreated surfaces do not stick together and, secondly, coefficients of friction range between* $\mu \approx 0.2$ *and* $\mu \approx 0.7$*. In regard to plastic contact spots it should be added here that these, too, are prevented from sticking by adsorbed moisture but that in their case the above range of friction coefficients is explained by the conditions of subsurface deformation (see ref. 11).*

The importance of the non-stick condition and limited range of friction can hardly be overestimated: We tend to take it for granted, and our daily activities depend on it, that we can hold a cup, walk on flooring, put on clothing, etc. etc. without either all surfaces sticking together like flies on fly paper, or slipping as on ice. Those would be the conditions for $\mu > 1$ *and* $\mu < 0.1$*, respectively. It is therefore very fortunate that moisture films are almost always incidentally present on electrical contacts and automatically provide protection against cold-welding while offering very nearly the minimum possible film resistance. Practically, for sliding electrical contacts we might wish for smaller* μ *values than provided by moisture films. Yet the discussed research convinces us that it is pointless to search for conditions that will provide such lower* μ *values, except if we are prepared to use artificial lubricants and as a consequence have to accept much higher contact resistances. The only alternative would be electrically conductive lubricants unless one is able to limit the lubricant film thicknesses to about 0.5nm or less. Specifically, graphite or* MoS_2 *lubrication can roughly halve the friction but the product of film thickness and resistivity is so large that it increases the contact resistance several-fold.*

We thus conclude that incidental or deliberate water lubrication is an excellent option for high-performance contacts in which large current densities have to be transmitted at low loss. It would be a great boon, and it is not impossible although unlikely, to identify a lubricant which for such purposes is still superior to adsorbed water. Superiority in this connection would mean either offering a reduced coefficient of friction without a great film resistivty increase or, even more importantly, useability to higher temperatures and/or lower ambient pressures than adsorbed moisture. Since our research has revealed what the needed properties of such a lubricant would have to be, we have given this possibility a great deal of thought already. So far have been unable to come up even with a distant competitor and are pleased, instead, to have optimized water lubrication..

Investigation of the Role of Adsorbed Moisture in Graphite Lubrication (ref.12)

Graphite lubrication of metals is of critical importance for the extremely widely used electrical brushes made of compacted mixed metal and graphite powders. This fact caused our interest in trying to more deeply understand the functioning of graphite lubrication, even more so because graphite lubrication of metals also strongly depends on moisture. Namely, as has

been known since WW II, electrical brushes made of graphite "dust" and become abrasive unless a minimum of moisture is available. In WW II this became a serious problem in high-flying aircraft and in space applications. Although ways have been found to work around that difficulty, partly by eliminating sliding contacts, partly by substituting molybdenum disulphide, the mechanism by which moisture facilitates graphite lubrication remained unknown. We have studied the problem and, as ref. 12 documents, the effect comes about through moisture adsorption films at the basal planes of graphite (as well on metals in accordance with the previous section) as follows:

The adsorbed moisture lowers the surface free energy of the basal plane of graphite so that it becomes shearable at stresses typically lower than the shear strength of the lubricated metals. By contrast, without adsorbed moisture the stress necessary to shear the graphite is substantially higher than for the metals. Further, adsorbed moisture films on graphite and on metal bond together so that the graphite adheres to the metal. In the presence of adsorbed moisture, therefore, the contact spots of metals are protected by graphite layers which in the course of sliding shear into ever thinner lamellae, much like a pack of playing cards. Only when thus the graphite layer at any particular contact spot has become very thin will the underlying metal shear, too. Thereby fresh metal surface becomes exposed to which fresh graphite adheres and the process repeats. The result are "pads" of very thin alternating layers of graphite and metal. These pads, once they are sheared off, form the bulk of the wear debris that can be collected. In the absence of moisture, however, the graphite is harder than the metal and does not cling to it but abrades it. A certain amount of metal abrasion takes place in any event through graphite particles which accidentally become embedded in the metal surface with their basal plane nearly normal to the interface. These act much like the cutting tool in a lathe and produce characteristic slivers of metal wear debris. In fact, the above process was inferred from a careful analysis of wear debris obtained from samples run under different sliding conditions. A summary of this work is also contained in ref. 1, an invited paper on the occasion of the Holm Achievement Award to the Principal Investigator.

Sub-Surface Deformation of Materials at Sliding Interfaces (Refs. 13 through 23)

An extremely important aspect of sliding electrical contacts is wear. Even the best electrical brushes in regard to electrical performance will not be acceptable if their wear life is too short. This is a particular challenge for metal fiber brushes, the focus of interest in this project, since in line with the preceding sections they are unlubricated. A better theoretical understanding of the processes which give rise to unlubricated wear is therefore urgently needed. Central here is the generally accepted fact that wear arises from sub-surface deformations at and about the contact spots. Our own research has shown that to a first approximation, and certainly before the formation of any particular tribo-surface films, this sub-surface deformation is the same as that which takes place in bulk under similar conditions of stress and strain. In fact, based on this insight one may deduce the distribution of sub-surface stresses in worn samples from the microstructure[13].

From the above set of circumstances derives the interest in this project for expanding the under-standing of correlations between microstructure and plastic deformation in general[14-16]. Of

particular concern in this connection are multi-slip and large deformations[17-20], as well as high strain rates[21], since these conditions are characteristic for the sub-surface strains of tribological samples. Another correlated interest is in the involvement of very thin layers of contaminants which may become trapped at the contact spots, e.g. of adsorbed water or oxygen. According to a quite recent discovery[22,23], such layers can greatly add to the strength of a material but also cause worksoftening, i.e. an instability. It may be noted here that the numerous publications referred to in the present section have not added significantly to the cost of the project but are more of a kind of bonus since almost no salary support was involved.

Practical Significance - *In constructing high-performance sliding metal-metal contacts we must try to reduce sub-surface deformation at contact spots as much as possible since this inevitably gives rise to hardening and wear. The above research proves that the mechanical response of the tribo layers at contact spots conforms to the general behavior of dislocations. It follows that the option of reducing the contact spot sizes and loads to the point of elastic deformation (compare Ref.1), so as to inhibit dislocation generation and motion, remains the most desirable for wear rate reduction . However, in accordance with the section on adsorbed moisture, contact spot reduction below, say, 1μm diameter, is probably useless on account of the excess "buried molecules" that will result and will unduly increase the contact resistance. The value of the research in this section lies thus in providing a sound basis for making this type of judgement.*

Automatic Brush Testing and Studies on Optimal Running of Brushes (Refs.1, 24-26)

For the practical success of electrical brushes a number of conditions have to be met. The impact of theory in achieving success in meeting some of these is contained in ref.1. First and foremost, electrical brushes should be non-toxic, have low electrical bulk and contact resistance, have adequate wear life, and be applicable at low enough loads that they do not damage the slip-ring and do not cause large amounts of friction heat. Depending on conditions they should have resistance to incidental contamination of the running surfaces, adapt to reversal of running direction, be capable to be run at high speeds and/or be capable of running on commutators.

A wide range of tests with detailed data collection and preferably extending over days or weeks is required to assess those various aspects of brush performance. References 24-26 relate to such testing. Specifically, ref.25 describes the system for long-term brush testing in controlled atmospheres which has been designed and built in our laboratory. It includes the facility to make pre-programmed changes of speed and current strength, with automatic data collection on resistance and wear. The schematic of the apparatus may be seen of the front page of ref.25 and is reproduced as figure 8.

A considerable part of the whole effort under this project has been spent on developing that system of which we now have two mildly different versions in our laboratory. These testers are invaluable and without them much of our work would have been virtually impossible. Albeit the research in ref.24, which establishes the ability of metal fiber brushes to perform satisfactorily

under commutation, required a different experimental set-up and was practically completed before the start of the present project.

Examples of the test records obtainable with the equipment are shown in Figures 9 and 10 extracted from ref.25. They concern a pair of copper-graphite brushes under 5N normal force on each brush sliding on a polished copper substrate at 10m/sec speed at an average 10 Amp current that was reversed every hour. Figure 9 records a "ramping", i.e. an interposed brief current/voltage curve during the 20hr test. As will be seen, the anodic, i.e. positive brush has the higher resistance which establishes itself rather fast but not instantaneously. Also note the non-ohmic behavior of the contact resistance. This is a sure sign of ionic conduction and in order to judge this aspect rampings are performed.

The similar slopes of the curves for the left and right brush in figure 10 indicate the dimensionless wear rate of $4x10^{-10}$ which is close to the top performance of monolithic metal-graphite brushes, but dropping off with speed and current density. The vertical offset between the two curves in figure 10, seemingly indicating an initially high wear rate of the left brush, is due to wearing-in and may be discounted.

Practical Significance *- The development of novel electrical brushes requires long-time testing in which under controlled currents and speeds electrical losses, friction and wear are recorded automatically, since personal record keeping is expensive and not less reliable. Until the development of the described apparatus no suitable equipment was available. It is confidently expected that it will prove very valuable in our and many other laboratories in the future.*

Development of a New Metal Fiber Material for Sliding Electrical Contacts (Ref. 26)

A major part of the funding was expended on the development of an improved metal fiber brush material. This effort had begun much earlier and was concurrently supported by the David Taylor Research Center, Annapolis. It has not yet been published, partly because it is not yet complete and partly because it may have commercial applications. Even so, at this stage success seems assured in overcoming a previous serious limitation of metal fiber brushes, namely what we have dubbed "the mink toothbrush problem" as follows:

For lowest possible electrical resistance and wear rates, metal fibers should be very thin, e.g. 20μm, while the optimal aspect ratio of length to thickness is about 100 and the optimal packing fraction of fibers is about 20%, all as described in our earlier patents[27,28]. However, the length of the fibrous part of such brushes if constructed painter's style is evidently only a few millimeters, and even minor wear will cause their performance to deteriorate sharply. It was therefore decided to make metal fiber brushes in which fibers of the desired dimensions are statistically interconnected among near-neighbors. Using rods of such material for brushes, microscopically at the running surface the wanted electrical and wear behavior is obtained but macroscopically the fiber material can have any arbitrary length and be worn through any arbitrary distance without change in the local behavior. We are glad to report that we have been able to

make some highly successful metal fiber brushes of such material and that the same type of material could be used for revolutionary EML armatures when the interstices are filled with a suitable material.

Figures 11 and 12, taken from ref. 26, show test results obtained with a brush pair of the above construction run at 15m/sec at a current of 100 Amps with deliberate water lubrication via forced moisturization of an ambient CO_2 atmosphere. As seen, the dimensionless wear rate is different for the positive and negative brushes, namely about $6x10^{-11}$ and $1x10^{-11}$, respectively. This is either due to ion transport through the metal or to slow electrochemical attack of the positive brush through OH^-.

The very large improvement of brush performance of the fiber brushes over the monolithic metal-graphite brushes will be seen from comparing figures 11 and 12 with figures 9 and 10: In spite of the much higher current density and higher speed of the fiber brushes, their dimensionless wear rate is roughly ten times slower and their ohmic resistance is only a few percent of that of the monolithic brushes!

Practical Significance - The performance of the newly developed metal fiber brushes is very superior to that of the best commercially available brushes, namely monolithic metal-graphite brushes. They are capable of very much higher current densities, have much lower electrical noise, can be operated at much higher speeds, wear more slowly, and waste very much less Joule heat than old-type brushes. They therefore should have a great future. Besides the material can be adapted for revolutionary EML armatures when the interstices are filled with suitable materials.

CONCLUSION

Overview

In line with the traditions of university research as well as with the initial proposal for the project which is herewith concluded, most of the very valuable results have been published in the open literature so as to be of maximum benefit to others. As a consequence, under sponsorship of this contract twenty three papers were published in the international literature. Below, they have been listed in chronological order of their completion. In the same order and with same numbering, the title pages of those papers, and thus also their abstracts, are reproduced on subsequent pages. Their perusal can add information beyond that contained in the present report. Additionally, thirteen invited lectures and eleven contributed lectures on various aspects of this research were delivered at Universities, Research Laboratories and International Conferences by the Principal Investigator and co-workers.

Not so far published, with a view to be reserved at least with some adequate lead time for the particular benefit of our sponsors, i.e. DARPA and the Navy Annapolis laboratory who co-sponsored this work, have been our development of the novel metal fiber brush material. This

could have very great benefits, firstly, for the development of improved armatures for rail launchers in accordance with a proposal presented to Picatinny Arsenal in the summer of 1992 and, secondly, for the development of homopolar motor/generator ship drives. We continue to work on the latter project.

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STICK-SLIP/SMOOTH SLIP AS A FUNCTION OF AMBIENT GASES AND PRESSURES DISPROVING PREVIOUS MODELS OF ADHESIVE WEAR

CHAO GAO, DORIS KUHLMANN-WILSDORF and DAVID D. MAKEL
Department of Materials Science, University of Virginia, Charlottesville, VA

ABSTRACT

Five different slip modes have been identified for bundles of copper fibers sliding on a smooth copper substrate in atmospheric air, argon and nitrogen at pressures from atmospheric to 0.01 Torr. These are stick-slip, variable sliding, intermittent stick sliding and two kinds of smooth sliding, one apparently a basic property of clean surfaces and the other due to contaminants. These forms of sliding are rather persistent once established, and they follow some trends. Specifically, low-pressure smooth sliding is coordinated with a value of the coefficient of friction (μ) near 0.15 and is seen when the surface film is exceptionally thin, while intermittent stick sliding appears to be due to "pads" on the substrate surface, and variable sliding to small particles caught in between the fibers and the copper substrate. However, the five slip modes are erratic in that under the same conditions one or another or yet a third may be observed, even though the electrical contact resistance (R) depends rather reproducibly on time, load, velocity, ambient atmosphere and pressure. That dependence indicates an equilibrium between film destruction through sliding and film formation, overwhelmingly through the presence of oxygen. In the stick-slip mode the difference between μ_{static} and $\mu_{kinetic}$ appears to be roughly proportional to μ - 0.15, i.e. the excess of the average value of the friction coefficient above 0.15 , being about 20% for μ = 0.3 and vanishing near μ = 0.15. During slip episodes, R spikes roughly in proportion to their magnitude. Some tentative interpretations are offered, based on the concept that μ consists of three additive components, namely due to the bulk (μ_{Bulk}), due to debris (μ_{Debris}), and due to scoring of surface films (μ_{Film}). At any rate, the conclusion that the results contradict all previous models of "adhesive" wear is inescapable.

INTRODUCTION

The conventional model of "adhesive" wear, based on the extensive pioneering work of F.P. Bowden and D. Tabor [1,2] and Holm [3], beginning in the nineteen thirties, is that of isolated contact spots formed at statistical interferences of asperities on the two sides. The model assumes that at the contact spots the two sides adhere via not further specified adhesive forces, and that the overall area of the contact spots is determined by the hardness (H) of the softer of the two sides and the normal force (P) pressing the surfaces together as

$$A = P/H \qquad (1)$$

The magnitude of the coefficient of friction (μ) is then accounted for by a finite shear stress, say S, necessary to break the adhesive bonds, or to shear an adhesively bonded interfacial film, for a requisite total tangential force of

$$P_T = SA = SP/H \qquad (2)$$

thus yielding

$$\mu = P_T/P = S/H \qquad (3)$$

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Determining Subsurface Stress Distributions in Tribological Samples from Dislocation Cell Sizes in Low Energy Dislocation Structures*

Y. ZHU† and D. KUHLMANN-WILSDORF

Department of Materials Science, University of Virginia, Charlottesville, VA 22901 (U.S.A.)

T. IMURA‡

Department of Metallurgy, Nogoya University, Nagoya (Japan)

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Abstract

The stress distribution that caused any observable low energy dislocation structure can be inferred from the scale thereof. For dislocation cells, the empirical formula $\tau \approx 10Gb/L$, with τ the resolved shear stress, L the average dislocation cell diameter, G the shear modulus and b the Burgers vector, is especially useful in this regard. As an example, it was applied to the subsurface dislocation cell size distribution underneath the wear scar on a copper foil 0.1 mm thick that had been glued onto a steel rod and then tested in a crossed-rods apparatus. The result confirms the theoretical expectation that the minimum required thickness, when foils are used to simulate the tribological behavior of bulk material, is at least twice, and more safely three times, the average contact spot diameter.

1. Introduction

Frequently, it is of considerable interest to determine the stress distribution which caused a particular plastic deformation without any realistic possibility for direct measurement, *e.g.* after a non-reproducible occurrence, and/or when requisite input parameters for a theoretical calculation are unknown. Examples are explosive deformations and subsurface deformations caused by friction and wear. In such situations, whenever the microstructure can be investigated, the typically predictable decrease in the scale of low energy dislocation structures with increasing stress can often be used to determine the stress distribution.

The particular case presented in this paper is a study of the subsurface stress distribution in thin copper and α-brass foils that had been subject to friction in a crossed-rods apparatus while glued onto a hard steel rod. The object was to find out to what extent the tribological behavior of bulk material, surface coatings and modified surface layers such as through ion implantation, for example, can be simulated in that or similar apparatuses by means of thin foils that are suitable for subsequent transmission electron microscopy (TEM) examinations.

The problem to be addressed is that the mechanical behavior of surface layers subject to sliding friction can be modified by the hardness and plastic deformability of the underlying material since, typically, plastic deformation at contact spots and underneath wear tracks penetrates by about one contact spot diameter into the subsurface [1, 2]. It was therefore expected that, to simulate the behavior of bulk parts, the foil thickness ought to be at least twice, and more safely three or more times, the expected diameter of the contact spot, in order to be sure that the specimen size does not falsify the results. Also, it seems reasonable to conduct such simulations with rods of a hardness similar to that of the underlying material in the actual case. Even so, a so far unknown extra safety margin, *i.e.* from a theoretically seemingly sound value of double the contact spot diameter to three or more times, is suggested because of unavoidable momentary fluctuations of the contact spot size about its average value, *e.g.* as through local variations in

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†Present address: Brookhaven National Laboratory, Upton, NY 11973, U.S.A.

‡Present address: Aichi Institute of Technology, Toyota-City, Aichi, Japan.

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Theory of Plastic Deformation:— properties of low energy dislocation structures*

D. KUHLMANN-WILSDORF

Department of Materials Science, University of Virginia, Charlottesville, VA 22901 (U.S.A.)

(Received February 3, 1989)

Abstract

Work-hardening phenomena are based on the very fundamental principles (i) that at the position of every dislocation axis the respective resolved shear stress cannot exceed the friction stress, including the self-stress of bowing dislocations, and (ii) that always that structure forms which among those accessible by the dislocations minimizes stored energy per unit length of dislocation line. Such dislocation structures have been named LEDSs. The corresponding work-hardening theory, the mesh length theory, is applicable to all materials deforming via gliding dislocations and to all types of deformation. Results previously achieved with the mesh length theory are summarized, and a number of new developments are discussed. Depending on the dislocation structures formed, the work-hardening behavior differs. Easily intersecting glide causes dislocation cell structures with almost dislocation-free cell interiors delineated by dislocation rotation boundaries. Pronounced planar glide causes Taylor lattices characterized by local planar order parallel to the one or perhaps two most highly stressed glide plane(s), no systematic lattice rotations, and overall uniform dislocation density. The most widely observed basic features of work hardening are explained in general terms. Specific applications are indicated for layer-type crystals, h.c.p. single crystals, single-crystal and polycrystalline pure f.c.c. metals and α-brass-type alloys, precipitation-hardened materials and steels. Included are the different stages of work hardening, dynamical effects in low temperature plasticity, the general characteristics of grain boundary strengthening and the Hall–Petch relationship. In addition, proposed explanations for (i) glide system interactions in polyslip resulting in microbands and affecting texture formation, and (ii) creep without stress dependence of dislocation density, are discussed.

1. Introduction

Undeservedly, work-hardening theory has the reputation of being difficult or obscure. This is not true, at any rate not for the mesh length theory of work hardening, the foundation and basic equations of which have remained unchanged since its inception in 1962 [1]. No significant additions had been made to it between 1966 [2] and 1980 [3], but there have been several important developments recently [4–7].

The theory has been variously surveyed in past references [8–10]. Some significant recent results are not included in any of these. Even more importantly, although from the outset [1] and consistently throughout the position has been taken that all types of materials, deformations and dislocation structures may be interpreted by means of the mesh length theory, whether in unidirectional or fatigue-type deformation [2, 8, 9] provided only that deformation occurs through dislocation glide, detailed discussions in regard to work hardening have been restricted to one-phase materials which develop a dislocation cell structure.

In the past, polycrystals, multiphase materials and those deforming with Taylor-type dislocation structures, as result from planar glide, have been neglected. Therefore it seemed worthwhile to specifically include such materials and summarize the present stand of the theory in regard to unidirectional strains as comprehensively and succinctly as possible, adding some facets not previously published. References are kept to a minimum for brevity and since the literature prior to the mesh length theory was thoroughly sur-

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III.1

MICROSTRUCTURAL INSTABILITY IN METAL-GRAPHITE LUBRICATION FILMS

D. Kuhlmann-Wilsdorf and D.D. Makel

Department of Materials Science, University of Virginia
Charlottesville, VA 22901, USA

INTRODUCTION

Sliding friction and wear occurs at a restricted number of contact spots whose total area typically is related to the impression hardness of the material (H) and the normal force across the interface (P) as

$$A = P/H \tag{1}$$

Thus the microscopically contacting area, i.e. A, is normally very much smaller than the macroscopic area of contact between the interacting surfaces, and the local pressure at the contact spots, averaging H, is very much larger than the macroscopic pressure. It is thus the behaviour at the contact spots which determines the coefficient of friction, the interfacial electrical resistance and the wear rate.

Research on friction and wear is complicated by the fact that during sliding the interface at the contact spots is almost never accessible to direct investigation, and post-hoc inspection rarely even reveals as much as the position, let alone the number and size of the contact spots, which tend to move about the interface in any event. Matters are further complicated because microscopically the two sliding materials are not in direct contact even at the contact spots but are separated by one or more interfacial film, sometimes through deliberate lubrication, sometimes through spontaneous reactions at the interface. Thus the elusive interfacial films often control the friction and wear behaviour. In view of the wide-ranging use of graphite as a solid lubricant, both for general purposes and for monolithic (one-piece) electrical brushes, interfacial films which are formed in the course of graphite lubrication are of particular interest. This interest is still heightened because of the peculiarity of graphite to require moisture or, lacking this, at the least some other condensable vapour, without which graphite loses its lubricity. In that condition graphite tends to wear away at a catastrophic rate through "dusting" and can act as an abrasive.

The phenomenon of dusting of graphite first aroused urgent concern in World War II, when essential electric motors and other equipment relying on graphite brushes failed in high-flying aircraft. As is discussed here, the dusting phenomenon is

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DYNAMIC EFFECTS IN THE MESH LENGTH THEORY OF WORKHARDENING

D. KUHLMANN-WILSDORF

Department of Materials Science, University of Virginia, Charlottesville, VA 22901, U.S.A.

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Abstract—According to the mesh length theory of workhardening, low-temperature strain rate effects in materials exhibiting a dislocation cell structure are due to the simultaneous operation of a number X of super-critically bowing links in the average, typically roughly equiaxed, cell of diameter L. The corresponding length of mobile dislocations per cell is then LX. Defining $g = L/\bar{l}$, with $\bar{l}$ the average link length in the cell walls, dislocation cell breakdown is expected for $X_{max} \approx 0.3\,g^2$, on the criterion that at the most 50% of all cell wall dislocations may be simultaneously destabilized and therefore at most 10% of all possible dislocation sources may be activated simultaneously since each destabilizes four adjoining links besides itself. When $X = X_{max}$, the mobile dislocation density within the cells is about 30% of that in the walls, but significant interactions and thus extra hardening is expected only if the dislocation density in the cell interiors is about sixteen times the cell wall dislocation density. Therefore the mobile dislocations can add little, if anything, to the permanent strain hardening. However, on account of the decrease of average source length with increasing X a transient increase of flow stress and workhardening coefficient arises which typically amounts to a few percent per ten-fold increase of strain rate. Mobile dislocations remaining in the cell interiors decrease the elastic modulus and can give rise to anelastic creep as well as to recovery effects. Numerical estimates are in good agreement with observations.

Résumé—Selon la theorie de la longueur de maille du durcissement par écrouissage, les effets de vitesse de déformation a basse température dans les matériaux ayant une structure de dislocation cellulaire sont dûs a l'action simultanée d'un nombre X de chainons en courbure siur-critique dans la cellular moyenne, approximativement equiaxiale, de diametre L. La longueur correspondante de dislocations mobiles par maille est donc LX. En posant $g = L/\bar{l}$, $\bar{l}$ étant la longueur moyenne des chainons dans les parois des mailles, la rupture des mailles de dislocations est attendue pour $X_{max} \cong 0.3\,g^2$ en se basant sur le critère suivant: au maximum 50% de toutes les dislocations de paroi peuvent être simultanement déstabilisées et par conséquent au plus 10% de toutes les sources de dislocations possibles peuvent être activées simultanément puisque chacune déstabilise les quatre chaines attenant à celle-ci. Quand $X = X_{max}$, la densité de dislocations mobiles à l'intérieur des mailles est environ 30% de celle des parois, mais des interactions importantes et donc un durcissement supplémentaire ne sont attendus que si la densité de dislocations à l'intérieur des cellules est environ 16 fois celle des parois. Donc les dislocations mobiles ne peuvent que peu participer à l'écrouissage permanent. Cependant, par suite de la décroissance de la longueur de source moyenne lorsque X augmente, on observe une élévation transitoire de la contrainte d'écoulement plastique et du coefficient de durcissement par écrouissage. Cette augmentation est typiquement de quelques % si l'on multiplie par 10 la vitesse de déformation. Les dislocations mobiles restant à l'intérieur des mailles diminuent le module élastique et peuvent donner lieu à un fluage anélastique aussi bien qu'à des effets de restauration. Les estimations numériques sont en bon accord avec les observations.

Zusammenfassung—Nach der Maschenlängentheorie der Verfestigung folgen die Dehngeschwindigkeitseffekte in Materialien mit Zellstruktur bei tiefen Temperaturen aus der gleichzeitigen Aktivität einer Anzahl X von überkritisch ausgebauchten Verbindungsversetzungen in der mittleren, typischerweise etwa gleichachsigen Zelle mit Durchmesser L. Die entsprechende Länge beweglicher Versetzungen pro Zelle ist dann LX. Mit $g = L/\bar{l}$, wobei $\bar{l}$ die mittlere Länge der Verbindungsversetzung in den Zellwänden ist, kann der erwartete Zusammenbruch der Zelle mit $X_{max} \approx 0.3\,g^2$ beschrieben werden; Kriterium ist, daß maximal 50% sämtlicher Versetzungen in der Zellwand gleichzeitig destabilisiert werden können, welches bedeutet, daß maximal 10% sämtlicher Versetzungsquellen gleichzeitig aktiviert werden können, da jede vier benachbarte Verbindungsversetzungen destabilisiert. Bei $X = X_{max}$ ist die mobile Versetzungsdichte innerhalb der Zellen etwa 30% derjenigen in den Wänden; allerdings wird eine beträchtliche Wechselwirkung und damit eine zusätzliche Verfestigung nur erwartet, wenn die Versetzungsdichte im Zellinneren etwa sechzehnmal größer ist als die Versetzungsdichte in der Zellwand. Daher können bewegliche Versetzungen nur wenig, wenn überhaupt, zu der vorhandenen Verfestigung beitragen. Betrachtet man jedoch die Abnahme des mittleren Quelldurchmessers mit zunehmendem X, dann tritt eine vorübergehende Zunahme des Verfestigungskoeffizienten auf, der typischerweise einige Prozent bei einer zehnfachen Dehnungsrate ist. Bewegliche Versetzungen, die im Zellinnern bleiben, verringern die Elastizitätskonstante und können zu anelastischem Kriechen und zu Erholungseffekten führen. Numerische Abschätzungen stimmen mit Beobachtungen gut überein.

INTRODUCTION AND BASIC EQUATIONS

According to the mesh length theory of workhardening applied to materials deforming with a dislocation cell structure [1, 2] (the most common of all stress-screened dislocation structures, whose acronym is LEDS for Low-Energy Dislocation Structure [3, 4]), there exists a one-to-one correspondence

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On Stick-Slip and the Velocity Dependence of Friction at Low Speeds

C. Gao

D. Kuhlmann-Wilsdorf

Department of Materials Science,
University of Virginia,
Charlottesville, VA 22901

Stick-slip is commonly ascribed to a difference between the static and dynamic coefficients of friction or at the least a strong negative slope of the friction/velocity curve at very small relative speeds. Other types of variable sliding have been ascribed to irregularities in local friction coefficients, to the excitation of resonance frequencies in oscillatory systems, and to local heating at contact spots. In the course of ongoing studies of metal-metal friction and contact resistance in the hoop apparatus, stick-slip, smooth sliding, somewhat disturbed harmonic oscillations, and a novel type of sliding dubbed "negative stick slip" have been examined. The coefficient of friction (μ) is again found to drop with decreasing ambient pressure, and the velocity dependence of μ determined directly from smooth sliding in vacuum shows an unexpected steep rise at low velocities. Both of these observations are in contradiction with the adhesive model of wear. Negative stick-slip suggests a still more complex $\mu(v_{rel})$ dependence which, however, appears to be compatible with the measurements. At any rate, negative stick-slip cannot be explained by any previously proposed models.

Introduction

Stick-slip is a widely observed phenomenon that has a number of significant practical consequences, especially in connection with potentially oscillatory systems, e.g., the violin string excited by a bow. The most widely accepted cause for stick-slip is a difference between the values of static and dynamic coefficients of friction, wherein the static coefficient (μ_s) is larger on account of adhesive bonding (Bowden and Tabor, 1973; Rabinowicz, 1965).

According to Rabinowicz (1965), also significant local variations in the value of the coefficient of friction can give rise to stick-slip, provided that there be only one or a very few contact spots. In addition to "regular stick-slip" caused by a sizeable difference between the static and dynamic coefficients of friction, and "irregular stick-slip" ascribed to local variations of the friction coefficient at low number of contact spots, Rabinowicz (1965) discusses one further type of variable sliding, namely "harmonic oscillations" which according to him are predicated on a decrease of friction with increasing velocity. Should a technologically important example of such be the "whistling" and "chattering" of electrical brushes (Holm, 1967; Shobert, 1965), however, then they are due to an excitation of resonance frequencies in an oscillatory system, since as discussed by Shobert (1965) and Holm (1967) brush chatter, like the squealing of chalk on a blackboard, does not depend on a negative slope of the friction-velocity curve. Lastly, in this brief survey of irregular or stick-slip modes previously treated in the literature, one may mention oscillations due to variations of the coefficient of friction on account of local heating which reduces the shear strength at the contact spots (Maksimov, 1988).

Oscillations of sliding systems and stick-slip are generally highly undesirable in technological applications. The elucidation of the responsible mechanisms can therefore be valuable in efforts to reduce their incidence, a point specifically addressed by Shobert (1965), Rabinowicz (1965) and Holm (1967). Granting this, there is evidently still much to be learned, since in ongoing experiments in this laboratory, variable slip has been observed under conditions which are not explained by any of the mentioned hypotheses. Specifically, the number of contact spots in those experiments is very large so that variable stick-slip of the kind discussed by Rabinowicz cannot arise. Next, due to the large number of contact spots and low speeds, local heating at contact spots is entirely negligible. Finally, a new form of irregular sliding, dubbed "negative stick-slip" characterized by sudden accelerations from an almost constant sliding speed and apparently never before reported, has been observed, as will be further discussed below.

The Hoop Apparatus

In addition to the practical considerations emphasized above, the study of stick-slip is highly worthwhile because it is a promising tool for a deeper understanding of the processes

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Theory of Work-Hardening Applied to Stages III and IV

D. KUHLMANN-WILSDORF and N. HANSEN

Stage IV has become the accepted name for that work-hardening stage within which large plastic strains can occur at a very low, virtually constant work-hardening rate, as exemplified by cold rolling and wire drawing. By contrast, in the preceding stage III, the work-hardening rate decreases sharply with strain, whereas in the still earlier stage II, the work-hardening rate is also almost constant but has a high value. The classical paper by Langford and Cohen[1] on drawn iron wire is now recognized as one of the earliest studies of stage IV. Already in 1970, a detailed theoretical analysis of that work based on the mesh length theory was presented[2] which has stood the test of time, although in it the Langford and Cohen experiments were considered to represent stage II on account of the operation of similitude and the almost constant work-hardening rate. The present paper re-examines the 1970 theoretical interpretation in terms of stage IV behavior, which necessitates reinterpretation of stage III. Included in the present interpretation are more recent insights regarding dislocation behavior in so-called LEDS, low-energy dislocation structures. It is concluded that stages II and IV differ, because in stage II, cross slip is insignificant, while in stage IV, it is unlimited. Accordingly, cross slip is gradually established in the course of stage III. However, similitude appears to operate in all three stages. By extension of the argument regarding stages III and IV, it is seen that stages V and VI could follow, including similitude, through the establishment of climb.

I. INTRODUCTION

To the traditional three stages of work-hardening (of which stage I is observed only under special conditions, *e.g.*, single crystals in single glide), stage IV has been added recently.[3] It is characterized by an almost constant low work-hardening rate and its ability to accommodate large strains, as in wire drawing, torsion, or rolling.[1,4–7]

Idealized, the experimentally observed work-hardening coefficient, $\theta = d\tau/d\gamma$, in stages II, III, and IV may be represented[5,6] as in Figure 1, if τ is the resolved shear stress and γ the resolved shear strain, or, equivalently, $\theta^* = d\sigma/d\varepsilon$, with σ the macroscopically applied stress and ε the true engineering strain. The terms θ^* and θ, σ and τ, and ε and γ are related *via* the Taylor factor, M, such that $\sigma = M\tau$, $\varepsilon = \gamma/M$, and $\theta^* = M^2\theta$, with typically $M \approx 2.5$ to 3.

It has been reported[4,5,6] that for different testing temperatures and for several metals, the hardening rate at the transition from stage III to stage IV, θ_t, scales with the stress at the transition, τ_{IV}, or the stress at which θ would extrapolate to 0, τ_s. In that case, since in stage IV the work-hardening coefficient remains nearly constant,

$$\theta_{IV} \approx \theta_t = c\tau_{IV} \approx c\tau_s \qquad [1]$$

with θ_{IV} the hardening rate in stage IV and c a constant between 0.05 and 0.1. Equation [1] was substantiated in Reference 6 by means of a table based on various data in the literature, one of these being the study by Langford and Cohen[1] on tensile testing of iron wire after drawing to different engineering strains.

D. KUHLMANN-WILSDORF, University Professor of Applied Science, is with the Department of Materials Science, University of Virginia, Charlottesville, VA 22901. N. HANSEN, Department Head, is with the Metallurgy Department, Risø National Laboratory, DK-4000 Roskilde, Denmark.

Manuscript submitted November 4, 1988.

As early as 1970, the results obtained by Langford and Cohen[1] were the subject of a theoretical analysis based on the mesh length theory of work-hardening[2] and were found to be in close agreement with that. Now that stage IV has become of current interest, and, in particular, since dislocation behavior has been recognized to be understood most readily in terms of LEDS,[8] it seemed useful to review and expand that analysis in light of this new development. Actually, in the mesh length theory, the recognition that dislocations tend to arrange in mutually stress-screened structures (thereby minimizing their energy, which is the essence of the LEDS concept) has long been held as important.[9,10] Recently, however, that concept has been considerably refined and elaborated.

In the earlier analysis,[2] the various geometrical parameters necessary for the quantitative application of the mesh length theory were extracted from the experimental results by Langford and Cohen,[1] including a large number of original full-size micrographs kindly supplied by these authors. The work is now recognized as a case of stage IV, but initially it was termed stage II behavior[2] on account of the nearly constant work-hardening coefficient. It was found that similitude operated throughout the strain range investigated;[1,2] *i.e.*, the dislocation structures could be derived from each other through a shrinking in scale inverse to the stress which formed them.

The objective of the present paper will be to apply the theoretical analysis of this earlier paper[2] and the underlying basic theory[9] to stage IV behavior, including Eq. [1].

II. THE WORK-HARDENING COEFFICIENT IN THE MESH LENGTH THEORY

Very preponderantly in all types of dislocation formation, whether through crystal growth, epitaxy, transformations, or plastic deformation, dislocations are trapped in the form of LEDS,[8–11] which are free of long-range

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Deformation Structures in Lightly Rolled Pure Aluminium*

B. BAY

The Engineering Academy of Denmark, Department of Mechanical Engineering, Lyngby (Denmark)

N. HANSEN

Department of Metallurgy, Risø National Laboratory, 4000 Roskilde (Denmark)

D. KUHLMANN-WILSDORF

Department of Materials Science, University of Virginia, Charlottesville, VA 22901 (U.S.A.)

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Abstract

The dislocation structure of lightly rolled aluminium is free of substantial long-range stresses and thus is a low-energy dislocation structure (LEDS). It consists of ordinary cell walls, dense dislocation walls (DDWs) and microbands (MBs) which are stretched out along DDWs and are composed of small pancake-shaped cells. In one particular sample studied, MBs were found in the orientation of shear bands, although they are not observed macroscopically. Since the DDWs and MBs appear together as if forming one general feature they have been dubbed DDW–MBs. The structure can be explain on two hypotheses: (i) All volume elements enclosed by DDWs, including MBs, are blocks of dislocation cells sharing the same combination of active glide systems which, however, are fewer in number than would be needed to satisfy the Taylor condition fully, for the reason that the rate of work hardening increases with increasing number of simultaneously activated glide systems. (ii) MBs are formed later than the DDWs on which they are situated. They complement the deformation due to the earlier cell blocks towards a better approximation of the Taylor condition. It is considered that MBs assume the orientation of shear bands when the strain in them leads to geometrical softening.

1. Introduction

Three elements of dislocation substructures in lightly rolled pure aluminium have previously been reported [1, 2, 3]. These are (i) ordinary dislocation cells, defining mutually lightly misoriented volumes of almost dislocation-free material with misorientation across the individual cell boundaries of normally up to 2°; (ii) dense dislocation walls (DDWs) which are dislocation boundaries with, say, about three times higher average relative misorientation across them, and extending from several to many times farther than ordinary dislocation cell walls, so as to form one continuous boundary for several or even many dislocation cells; (iii) microbands (MBs) of a length similar to DDWs but composed of pancake-shaped much smaller cells which define a common boundary or narrow zone passing between regular dislocation cells, wherein one to four such small pancake-shaped cells (SPCs) may form the thickness of the MB. Gaps between SPCs are bridged by DDWs. Figure 1 is an idealized rendering of the types of dislocation substructure elements named above.

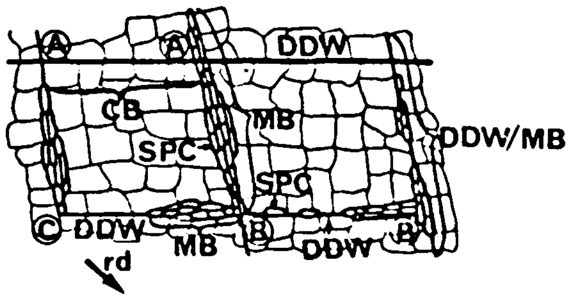

Fig. 1. Idealized microstructure in a thin foil from a longitudinal section of an f.c.c. metal such as aluminium, after rolling, including DDWs and MBs which are dubbed DDW-MBs when occurring in combination. DDWs are boundaries delineating CBs composed of ordinary dislocation cells. MBs are composed of SPCs in layers of 1 to 4 lying side by side. The rolling direction is marked by an arrow rd.

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Commutation with Metal Fiber Brushes

DORIS KUHLMANN-WILSDORF AND DANIEL M. ALLEY

Abstract—For many years it has been widely held that metal fiber brushes cannot be used on commutators because i) chopping action of commutator bars would casue fiber breakage and catastrophic wear, ii) current surges across adjoining bars would cause severe arcing and thus fast erosion. Recent experiments with copper fiber brushes in a protective argon atmosphere, using simulated commutation as well running them as working brushes in an electromotor, contradict both of these assumptions. No fiber breakage was observed, arcing was only moderately stronger than with carbon brushes, and the total dimensionless wear rate in the motor was only about twice that on a polished copper rotor under otherwise comparable conditions.

Introduction

The theoretical performance limits of metal fiber brushes are very high indeed, especially if the fiber diameter is made less than, say, 20 μm and the packing fraction F, i.e., the percentage of the macroscopic brush area which is occupied by fiber ends, is made relatively high but compatible with adequate fiber flexibility, say, 30 percent or so. In that case, electron tunneling about the periphery of contact spots makes a sizeable addition to the direct conduction through the contact spot area which would be computed for elastic load-bearing Hertzian contacts.

Holm [1] was the first to consider the peripheral electron tunneling effect and found that it increases strongly with decreasing contact spot radius. However, for contact spot radii as contemplated by Holm, i.e., 5 μm or more, the contribution of peripheral tunneling currents to the total conduction is negligible. For metal fiber brushes, on the other hand, the contact spots can become so very small that the effect is not only sizeable but becomes dominant [2]–[6]. Fig. 1 demonstrates this for an assumed film resistivity of $\sigma_F = 10^{-12}\,\Omega\cdot\text{m}^2$ which for clean metal surfaces is typical [2]–[4].

The extremely high current densities and/or low contact voltages which in this manner can be achieved at least in principle are not the only attraction for attempts to transform metal fiber brushes from a laboratory curiosity into a technological reality. Rather, the basis of the described high contribution of tunneling currents, namely the existence of a very large number of elastic (as contrasted to plastic) contact spots [2], [3], has the correlated consequence of potentially very low wear rates. These were indeed achieved by Reichner who obtained dimensionless wear rates of 5×10^{-11} [7] and 1.9×10^{-11} [8] for copper fibers on a smooth copper substrate in a protective atmosphere. Independently, Boyer, Chabrerie, and Saint-Michel [9] obtained a 10^{-11} wear rate at 100 m/s for bronze fiber brushes, again in a protective atmosphere. Finally, Sohre [10] reported virtually indefinite lifetimes of fiber brushes used to conduct shaft currents under quite adverse conditions and at speeds up to 150 m/s.

Add to these potential advantages of metal fiber brushes the ability to achieve very high speeds [3], [11] and extremely low electrical noise levels [3], and it is obvious why the replacement of monolithic graphite or metal-graphite brushes by metal fiber brushes is intrinsically very desirable. Albeit, suitable metal/atmosphere combinations to adequately control the interfacial film over long periods of time have not yet bee developed, except for the quite low current densities encountered in shaft current conductance [10].

Anticipated Impediments to Using Fiber Brushes on Commutators

The several difficulties variously encountered with monolithic brushes, which prompt the desire to find a substitute, include erratic wear rates, occasionally too high resistance causing unduly high voltage drops and thus heating, high electrical noise, and at any rate limited capability to perform at speeds above, say 25 m/s. If therefore metal fiber brushes should become practical in the future, one may confidently expect that they will outperform monolithic brushes in these respects. However, it has long been supposed that, for two reasons and in principle, metal fiber brushes cannot replace monolithic graphite or metal-graphite brushes when commutation is involved. If so, the potential use of metal fiber brushes would be severely restricted. Therefore, the object of the present study was to test the effects of commutation on fiber brushes.

Metal fiber, or better metal wire, brushes were standard equipment until the introduction of monolithic graphite brushes. It seems that the difficulties encountered in commutation with metal wire brushes were a potent reason for the phasing out of metal wire brushes, to the point that their earlier prevalence was forgotten. Nowadays, the oid metal wire brushes are only occasionally seen, more in museums than in actual practice.

The initial reason for the reintroduction of metal fiber brushes [2]–[6], [9], at least in regard to [2] and [3], was their predicted superior performance for fibers thin enough to yield elastic rather than plastic contact spots. This was indeed

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D. Kuhlmann-Wilsdorf is with the Department of Materials Science, University of Virginia, Charlottesville, VA 22901.

D. M. Alley was with the Department of Materials Science, University of Virginia, Charllottesville, VA 22901. He is now with Martin Marietta, Ocean Systems Operation, Glen Burnie, MD 21061.

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IEEE TRANSACTIONS ON COMPONENTS, HYBRIDS, AND MANUFACTURING TECHNOLOGY, VOL. 14, NO. 1, MARCH 1991

Adsorption Films, Humidity, Stick-Slip, and Resistance of Sliding Contacts

Chao Gao and Doris Kuhlmann-Wilsdorf

Abstract—The effect of humidity on gold-plated contacts has been studied in the hoop apparatus using a solid slider and fiber bundles. The specimens slide smoothly (for significantly positive $d\mu/dv$), execute harmonic oscillations (for dv/dt near zero), or stick-slip (for significantly negative d/dv). High humidity and low speed favors stick-slip, low humidity, and high-speed smooth sliding. The tendency for stick-slip is greater for a solid slider than for fiber bundles. The electrical resistance is indicative of an about 0.5-nm thick adsorption film at the contact spots, independent of coefficient of friction, sliding mode, or ambient atmosphere including vacuum. Minute traces of contaminants can inhibit the humidity effect. The observations are explained on the model, that of adsorbed films, all but one monomolecular layer on each side are squeezed out from between load-bearing areas, and that the excess molecules flow about the contact spots during sliding. Electrical noise is due to minor variations of film thickness at the load-bearing areas. It is larger for a solid slider than for fiber bundles, and larger for stick-slip than other sliding modes.

Keywords—Contact resistance, adsorption films, humidity, electrical noise.

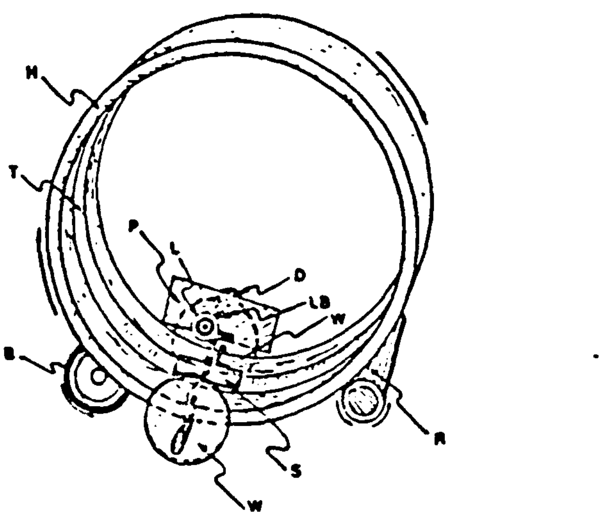

Fig. 1. In the hoop apparatus the sample (S) slides within the metal hoop (H) which is kept rotating at constant speed via the driving rod (R). On the other side of R the hoop is supported by a ball bearing (B). The momentary angular position of S is monitored by means of a beam of polarized light (LB) from a fixed light source (L) which passes through a polaroid (P) atop S onto a photodiode (D). The normal force between S and H is controlled by cylindrical weights (W) slipped onto horizontal rods shaped to let the center of gravity of S, P, rods, and W be in line with the interface. The sample is kept from falling out of the hoop by a barrel-shaped groove (T) and/or a light guide constraining P which is not shown. Also not shown are light wires and contacts for measuring the contact resistance.

I. Introduction

As a matter of practical know-how it is well known that electrical brushes perform better when the ambient atmosphere is humid. Humidity causes a reduction of electrical contact resistance, and in the case of brush materials containing graphite, reduces wear and decreases friction. In some recent papers, the well-known effect of humidity as an essential ingredient of graphite lubrication [1]-[3] has been explained in terms of bonding between adsorbed water films and metal, on the one hand, and graphite on the other hand [4], [5].

The parallel effect of moisture on metal-metal contacts is still unexplained. Here, too, humidity was found to be helpful in decreasing contact resistance, but friction is mildly increased, as was found from studies of metal fiber brushes [6]-[8]. In order to fill in this gap in our knowledge, a series of experiments were made in the hoop apparatus which is described in [9]-[11]. Fig. 1 illustrates its principle, namely that a rotating hoop provides what in essence is an infinitely long inclined plane on which a sample slides.

In view of the potential value of any knowledge pertaining to metal fiber brushes as well as on account of our extensive past experience, metal fiber brushes were tested, and for comparison purposes, a solid sample. Gold-plated copper was used for both samples and substrate in order to avoid complications through oxidation, and normal forces were made so low that wear rates are negligible over the whole extent of the tests, involving altogether on the order of 10 000 meters of sliding at speeds up to 3 cm/s on one and the same gold-platings.

The apparatus permits using controlled atmospheres at normal pressure and below, down to less than 0.01 torr. Various different atmospheres and different pressures were employed accordingly, but while with copper samples oxygen-free gases and vacuum pressures have distinctly different effects than laboratory air or oxygen [8], [11] no significant such differences were found with the gold-plated samples. Therefore, the data reported herein differentiate according only to humidity which indeed had distinct effects as will be seen, but independent of the carrier gas.

II. Experiments and Results

Somewhat surprisingly, it was soon found that the behavior of the sample as well as the contact resistance depended more strongly on the velocity of the hoop than can be readily explained. This is not obvious from Figs. 2 to 4, which show the resistance (R), coefficient of friction (μ), and electrical "noise" ($\delta R/R$ with δR the difference between the average extrema in $R(t)$ curves from the average value), respectively, as a function of both humidity (H) and hoop surface velocity (v_H). The sample was a triangle of similar bundles of 2800 each gold-plated

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The authors are with the Department of Materials Science, University of Virginia, Charlottesville, VA 22901.

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Automated Apparatus for Long-Term Testing of Electrical Brushes

Daniel M. Alley, *Member, IEEE*, Linda J. Hagen, Doris Kuhlmann-Wilsdorf, David D. Makel, and C. Grady Moore III

Abstract—The meaningful evaluation of electrical brushes, and even more so the development of novel electrical sliding contacts, can require testing for days, weeks, or months during which a variety of characteristics should be monitored under perhaps several different operating conditions. Normally this would involve a prohibitive input of manpower, and consequently long-term brush tests tend to be less than satisfactory. In response to this need, an automated testing system has been developed in which a personal computer both controls test parameters for a matched brush pair running on the same rotor according to a preselected program, and stores test data. Specifically controlled are the brush forces, brush polarity, and the current. Specifically monitored are the voltage drops across each of the two brushes, their wear, and the rotor temperature. Additionally, "traverses", meaning brief periods of ramping the current up and down between pre-selected limits while measuring the associated voltage drops, can be programmed into the tests. The duration of the various phases in complex testing programs as well as the intervals between data taking can be varied between seconds and months, but the system is switched off automatically when the voltage across either of the two brushes or the rotor temperature exceeds a preselected value. The accumulated data can be recalled in various graphical representations and program changes can be made at any time without interrupting the test.

Keywords—Brush testing, automation.

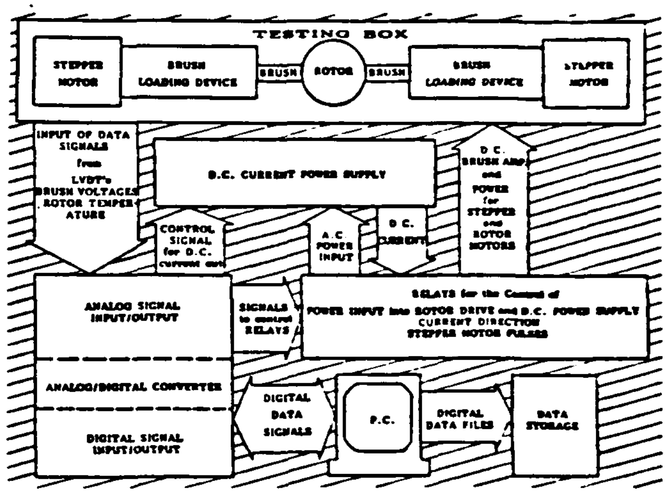

Fig. 1. Schematic of the architecture of the apparatus including its major components and their interconnections.

I. Introduction

Routine testing and, in particular, development of improved electrical brushes require control of the conditions which influence the brush/rotor interface, and accurate measurement of the performance parameters, not infrequently over extended periods of time. The apparatus first described in [1] and [2] and further discussed below, has proved to be very effective in meeting these requirements by allowing accurate control of sliding speed, current, brush force and atmosphere, and by providing for the measurement of the voltage drop at the interfaces and the wear rate during testing. This apparatus, however, must be continuously monitored and adjusted by a trained operator, thereby limiting the practicable duration of tests.

Numerous brush testing devices have been constructed by other researchers, e.g., [4]–[13], some of which automatically take data and can be left unattended for long periods of time. The present goals, however, include a higher degree of automatic operating parameter control, more test scheme flexibility, signal monitoring for the assessment of possibly damaging conditions, and algorithms for efficient data storage.

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D. M. Alley was with the University of Virginia, Charlottesville, VA. He is now with Martin Marietta, Ocean Systems Operation, Glen Burnie, MD 21061.

L. J. Hagen, D. Kuhlmann-Wilsdorf, D. D. Makel, and C. G. Moore III are with the Department of Materials Science, University of Virginia, Charlottesville, VA 22901.

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This paper describes an automated apparatus which fulfills the indicated needs by combining the brush test apparatus of [1]–[3] with a microcomputer which continuously controls the brush force, current magnitude, and current direction while taking and storing voltage drop, rotor temperature, and wear rate data. In order to prevent accidental damage to the apparatus or destruction of the brushes, the computer automatically aborts the test if temperature or voltage drops stray outside of preset ranges. For example, above some critical temperature, graphite-containing brushes are rapidly destroyed by dusting.

II. System Architecture

A. Overall Plan

The schematic of the system, shown in Fig. 1, comprises six major components: 1) the testing box, 2) the dc power supply for brush current, 3) the analog ↔ digital converter, 4) the "high current relay box", an assembly of control relays, 5) the microcomputer, and 6) data storage. A description of the components follows.

1) Testing Box: For brevity, the rotor and brush assembly, including the environmental enclosure in which it is housed as shown in Fig. 2, has been called the testing box. This includes all the hardware needed for adjusting the brush positions, adjusting the brush forces, regulating the rotor speed, measuring the rotor temperature, providing a current path through the brushes and rotor, and measuring the brush/rotor voltage drops. The design of this system has been described in [1] and has since proven to be very successful.

2) Power supply: Two alternative dc current supplies, for high and for low brush currents, are available. The low current

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OBSERVATIONS ON THE EFFECT OF SURFACE MORPHOLOGY ON FRICTION AND SLIDING MODE

Chao Gao, Doris Kuhlmann-Wilsdorf
Department of Materials Science
University of Virginia
Charlottesville, Virginia 22901, USA

ABSTRACT

Effects of humidity, surface roughness and contact spot size was studied in the hoop apparatus using a solid slider as well as bundles of 50μm diameter metal fibers (simulating a composite with a matrix very much softer than the reinforcements). All surfaces were gold-plated in order to minimize problems through oxidization, a constant normal force of 0.45N was applied, and hoop speeds varied between 0.02 and 2.8cm/sec. Even though unspecified adsorbed contaminants of less than one molecular layer on each side can have strong effects on the coefficient of friction, contact resistance and mechanical noise, no systematic differences between these could be detected for the two different samples, in spite of the fact that the contact spot size is about 1μm for the fiber bundles and 30 μm for the solid slider. The only clear-cut effects are (i) a markedly decreased tendency of the pseudo-composite for stick-slipping, and (ii) much greater electrical noise for the solid slider. It appears that, at least in this case, stick-slip was due to ordering of monomolecular water layers while the sample passes over them. For this effect, either sample or contact spot size differences could be responsible. Surface roughness differences, which were rather small in any event, did not noticeably influence the results.

INTRODUCTION

ELECTRIC METAL FIBER BRUSHES have much promise for practical applications (1-9). Tribological studies of bundles of fine metal fibers have therefore practical merit. Independent of practical considerations, however, metal fiber bundles are excellent samples for the study of fundamental tribological behavior including properties of adsorbed surface layers and wear chip formation (10). Optimal use is made of this opportunity when mechanical and electrical measurements are teamed in the so-called "hoop apparatus" (11-14). The reason for this is that the number of contact spots can be made so high that the electrical resistance is controlled by the interfacial films while the generally unknown "constriction resistance" is negligible. Therefore even subtle changes in very thin adsorbed films can be monitored on a moment-to-moment basis, with sampling frequencies as high as 100Hz.

Available results confirm a long-held conviction that among surface films, adsorbed moisture plays a decisive role, at the least for "clean" surfaces in the atmosphere. Correspondingly, studies of metal fiber bundles in the hoop apparatus have the potential of greatly furthering our understanding of monomolecular adsorbed water layers as well as other adsorption films. In the context of the present conference this is only of secondary interest, however. Instead, the potential of friction and resistance changes associated with adsorbed moisture as a tool for studying possible tribological effects of surface and contact spot morphology are exploited. For that purpose, in the context of the present conference, metal fiber bundles may be seen as a model fiber-reinforced composite with extreme difference between the hardnesses of matrix and reinforcements.

EXPERIMENTAL CONDITIONS

METHOD AND MATERIALS - The experiments were conducted in the hoop apparatus (11-13), i.e. on samples sliding within a short section of a horizontal metal tube which uniformly revolves about its center axis. In order to avoid complications due to metal oxidation (12), the hoop as well as the samples were of gold-plated copper. The fibers, of 50μm diameter, were formed into three 3mm diameter bundles of 2650 fibers each, and the solid slider was 2.1x1.7x 0.35cm.

All of the experiments reported herein were performed in laboratory air at ambient pressure but with the humidity controlled as variously indicated. This is no significant restriction

Ref. 13

EXPERIMENTS ON, AND A TWO-COMPONENT MODEL FOR, THE BEHAVIOR OF WATER NANO-FILMS ON METALS

CHAO GAO AND D. KUHLMANN-WILSDORF
University of Virginia, Dept. of Materials Science, Charlottesville, VA 22901

MRS Meeting, San Francisco, April 16-19, 1990
Symposium on THIN FILMS: STRESSES and MECHANICAL PROPERTIES.

ABSTRACT

Experiments on contact resistance and coefficient of friction of fiber bundles on a solid substrate in the hoop apparatus are reported, conducted in air at different humidities. The results suggest a two-component model in which a double molecular layer of adsorbed water exists at contact spots but thicker layers, depending on humidity, outside these. During sliding, therefore, rapid flow of adsorbed water molecules must take place about the contact spots. The combined effects of the moisture at the contact spots and of shear thinning of the moisture flowing about them can explain the results.

INTRODUCTION

Strong interest in the tribological behavior of recording heads and disks, as well as the development of techniques for the study of exceedingly thin films on atomistically smooth surfaces [1-3], has given rise to a wealth of new research into the mechanical behavior of surface films in the nano meter range. Impressive papers in this area have been reported at the recent STLE-ASME conference in Ft.Lauderdale, Oct. 16-19, 1989, for example, [4-6]. From these, as well as much previous less detailed evidence, it is clear that adsorbed water, in particular, can control or modify tribological behavior. Thus quite typically, high humidity in the ambient atmosphere increases the coefficient of friction [4,7,8] as also shown in Fig.1 for tests on samples that form the basis of the present paper.

Previous papers on the effects of adsorbed moisture tend to fall into two categories, those in which detailed studies are made on films while sliding speeds are in the micrometer per second range (a good literature survey on these is contained in [5]) and those which rely on less detailed measurements but in more realistic velocity ranges (e.g. in regard to "stiction" [7, 8]). As a result there is a large gap between knowledge of atomistic behavior of films at very low speeds and tribological behaviors of practical interest, e.g. at the high speeds of magnetic flyer/disk systems. The hoop apparatus, on which several papers have already been published [9-13], promises to fill this gap in that rather detailed measurements can be made, including on monomolecular films, and speeds can be varied between about 100 μm/s and 3cm/s.

EXPERIMENTAL METHOD

The hoop apparatus was used with the same sample configuration previously described [12,13]: Three parallel copper fiber bundles, mounted in a holder, and each consisting of 2650 about 1 cm long, 50μm thick fibers, were slid end-on within the hollow of a rotating, horizontal thin-walled copper tubing. In order to avoid complications of oxidation, both fiber bundles and tubing had been gold-plated. The three bundles were arranged in a holder in the form of a triangle with its apex in leading position and base parallel to the tube axis in trailing position, thereby defining a stable sample/hoop interface for sliding. As in previous studies, the angular position of the "sample"

8th International Conference
On Wear of Materials
April 7–11, 1991
Hyatt Orlando, Florida

Ref. 14a

ON THE TRIBOLOGICAL BEHAVIOR OF ADSORBED LAYERS, ESPECIALLY MOISTURE

by

Chao Gao, Doris Kuhlmann-Wilsdorf and Matthew S. Bednar

Department of Materials Science

University of Virginia

Charlottesville, VA 22901

ABSTRACT

The action of adsorbed molecular films, and in particular moisture, to affect friction and sliding mode was studied in the hoop apparatus. The samples were bundles of 50μm thick gold-plated copper fibers sliding on gold-plated copper, i.e. under gravity inside a gold-plated vertical copper hoop rotating at uniform speed about its horizontal cylinder axis. The results confirmed previous observations that the incidence of stick-slip increases with decreasing hoop speed and with increasing humidity, - in the present study in a nitrogen atmosphere. Also, stick-slip increases with increasing normal force and is much more persistent for bulk samples than for fibers. Additional information had been gained previously through detailed examinations of the momentary contact resistance. The data suggest that, although the thickness of adsorbed moisture films increases with humidity, at contact spots all except one molecular layer on each side drain out, regardless of humidity. Two contributions to the coefficient of friction (μ) result: (i) The displaced water flows about the spots and thereby adds an increment $\delta\mu_k$ which rises with humidity. At slow speeds $\delta\mu_k$ is proportional to sliding speed but shear thinning of the fluid causes a decrease of $\delta\mu_k$ at higher speeds. (ii) Capillary action of the moisture miniscus about the spots effectively adds to the applied normal force and thereby increases μ by an increment $\delta\mu_s$. Relaxation effects arise because neither moisture drainage nor equilibration of the miniscus is instant. The resultant different dependences of $\delta\mu_k$ and $\delta\mu_s$ on time, speed and on the spot size appear to explain the observations.

NOMENCLATURE

a	contact spot (or "a-spot") radius
A_+	normal component of a-spot area immersed in fluid
D	hoop diameter
F	fluid drag of sphere moving in a uniform fluid
F_c	capillary force on a-spot due to fluid film
F_d	fluid drag on contact spot due to adsorbed film
F_σ	normal component of surface tension force
g	acceleration due to gravity
H	humidity
L	normal force between sample and hoop
n	exponent (n = 2 and 3 for plastic and elastic a-spots)
N	number of contact spots of a sample
P	total load between sample and hoop
P_a	average load per contact spot
p_L	Laplace pressure due to meniscus
R	radius of asperity forming contact spot
R_m	radius of curvature of meniscus about contact spot
T	period of harmonic sample motion in hoop
v	relative velocity between sample and hoop
v_H	hoop speed
Γ	viscosity of adsorbed fluid film
Θ	momentary angular posion of sample on hoop
Θ_{eq}	equilibrium value of Θ in harmonic motion
ϕ	angle of immersion of a-spot in adsorbed fluid film
ϕ_1	wetting angle between fluid and contact spot
$\delta\mu$	average difference between μ_s and μ_k during one test
$\delta\mu_k$	contribution to μ due to fluid flow about contact spots
$\delta\mu_s$	contribution to μ by capillary action at contact spots
μ	coefficient of friction
$\bar{\mu}$	value of μ corresponding to equilibrium value of Θ
μ_{ave}	time average of μ
μ_{app}	value of μ corresponding to Θ, i.e. μ_{app} = arc tan Θ
μ_k	kinetic coefficient of friction, i.e. to continue motion
μ_s	static coefficient of friction, i.e. to start motion
σ	surface tension against air of adsorbed fluid

INTRODUCTION

Previous studies of samples in the hoop apparatus have revealed very intriguing effects of average sliding speed and humidity on the incidence of stick-slip in the hoop apparatus (1-5). In summary of rather extensive measurements it was found that stick-slip is suppressed beyond some limiting average sliding speed in the order of a few cm/sec, that in humidified but otherwise inert gases stick-slip increases with relative humidity regardless of the specific composition of the ambient atmosphere, and that the tendency for stick-slip increases with increasing size of the contact spots. Simultaneous measurements of the electrical contact resistance revealed spikes during slip episodes and slow decreases during rest periods, but otherwise relative insensitivity to humidity.

A model to acount for this behavior, and at the same time interprete the behavior of adsorbed molecular layers during unlubricated sliding in general and moisture in particular, was begun to be developed (3,5) but remained still incomplete. Also, as the understanding of the crucial parameters developed only gradually, the earlier data were not systematic. The intent of the present paper therefore is, firstly, to present a more systematic set of data and summarize the experimental results; secondly, to expand and refine the model.

This research is very important for a variety of reasons, besides fundamental theoretical interest. Most basically, adsorbed molecular layers on solids are ubiquitous except after thorough cleaning and degassing in high-vacuum. In our surroundings, oxygen and water are

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On the tribological behavior of adsorbed layers, especially moisture*

Chao Gao, Doris Kuhlmann-Wilsdorf and Matthew S. Bednar
Department of Materials Science, University of Virginia, Charlottesville, VA 22901 (U.S.A.)

(Received March 23, 1991)

Abstract

The action of adsorbed molecular films, and in particular moisture, to affect friction and sliding mode was studied in the hoop apparatus. The samples were bundles of 50 μm thick gold-plated copper fibers sliding on gold-plated copper, *i.e.* under gravity inside a gold-plated vertical copper hoop rotating at uniform speed about its horizontal cylinder axis. The results confirmed previous observations that the incidence of stick–slip increases with decreasing hoop speed and with increasing humidity, in the present study in a nitrogen atmosphere. Also, stick–slip increases with increasing normal force and is much more persistent for bulk samples than for fibers. Additional information had been gained previously through detailed examinations of the momentary contact resistance. The data suggest that, although the thickness of adsorbed moisture films increases with humidity, at contact spots all molecular layers except one on each side drain out, regardless of humidity. Two contributions to the coefficient of friction μ result.

(i) The displaced water flows about the spots and thereby adds an increment $\delta\mu_k$ which rises with humidity. At slow speeds $\delta\mu_k$ is proportional to sliding speed but shear thinning of the fluid causes a decrease in $\delta\mu_k$ at higher speeds.

(ii) Capillary action of the moisture meniscus about the spots effectively adds to the applied normal force and thereby increases μ by an increment $\delta\mu_s$. Relaxation effects arise because neither moisture drainage nor equilibration of the meniscus is instant.

The resultant different dependences of $\delta\mu_k$ and $\delta\mu_s$ on time, speed and on the spot size appear to explain the observations.

1. Introduction

Previous studies of samples in the hoop apparatus have revealed very intriguing effects of average sliding speed and humidity on the incidence of stick–slip in the hoop apparatus [1–5]. In summary of rather extensive measurements it was found that stick–slip is suppressed beyond some limiting average sliding speed in the order of a few centimeters per second, that in humidified but otherwise inert gases stick–slip increases with relative humidity regardless of the specific composition of the ambient atmosphere, and that the tendency for stick–slip increases with increasing size of the contact spots. Simultaneous measurements of the electrical contact resistance revealed spikes during slip episodes and slow decreases during rest periods, but otherwise relative insensitivity to humidity.

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CORRELATION BETWEEN DISLOCATION MICROSTRUCTURE

AND STATIC/DYNAMIC STRENGTH OF METALS

D. Kuhlmann-Wilsdorf

Department of Materials Science
University of Virginia, Charlottesville, VA 22901

"Modeling the Deformation of Crystalline Solids"
(Eds. T.C. Lowe, T. Rollett, P.S. Follansbee and G.S. Daehn
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Abstract

In plastic deformation, glide dislocations mutually trap into positions of stable force equilibrium, i.e. into low-energy dislocation structures (LEDS). In LEDS near-neighbor dislocations mutually screen their respective resolved shear stress components to the level of the frictional stress (τ_0) or less. As a result, the flow stress rises with dislocation density ç as $\tau = \tau_0 + \alpha Gb\sqrt{ç}$ where G is the shear modulus, b the Burgers vector and $0.1 \le \alpha \le 1$ depending on dislocation density and LEDS type. According to the LEDS principle, dislocations approach the LEDS of lowest energy per unit line length accessible to them. "Forest dislocations" arise in response to dislocation stresses and facilitate LEDS formation. The three most common LEDS are: (i) Dislocation cell structures, since 1914 known to crystallographers as the "mosaic block structure". They are composed of dislocation rotation boundaries (approximately) obeying Frank's formula. (ii) "Taylor lattices", i.e. quasi-uniform dislocation distributions without net Burgers vector content of which fatigue "loop patches" are the one-Burgers-vector form. (iii) Maze structures geometrically resembling cell structures but composed of multipolar boundaries without net Burgers vector content and thus not associated with relative crystal rotations. They are frequently seen in fatigue. The "ladder structure" in persistent slip bands is a one-Burgers-vector maze structure. As a result of the LEDS principle, Taylor lattices tend to transform into into cell structures, in fatigue via maze structures. Operation of the LEDS principle on wall-end stresses causes (i) the characteristic shape of maze structures with many T- and L-shaped wall joints, (ii) the mosaic block structure in lieu of isolated cells in a common matrix and (iii) the stress dependence of the average cell size $D \approx KGb/(\tau - \tau_0)$ with $K \approx 10$, independent of deformation conditions. In cell structures the workhardening coefficient is $d\tau/d\gamma \approx G\beta/2g$ with g the cell diameter in units of the average link length and β the trapped dislocation fraction. With increasing dislocation density g decreases from ≈ 100 to about 15, while β shrinks from about unity ultimately to zero. In tests, workhardening curves and fatigue hysteresis loops were found to closely conform to the theory. The LEDS theory also readily explains precipitation hardening, the dependence of yield stress on obstacle spacing, pre-yield anelasticity, the Hall-Petch relationship and strain-rate effects.

Introduction

The theory of mechanical strength and workhardening is intrinsically simple and has over the years been developed in considerable detail, to the point that few unsolved problems remain (1-3). Even so, the range of pertinent phenomena and details of dislocation behavior are formidable so that the appearance of complexity if not obscurity has persisted in the minds of quite a few researchers. The goal of the present paper is, therefore, to aid in the wider understanding of the theory by presenting only the basics, and these as succinctly and clearly as possible.

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Moisture Effects Including Stiction Resulting From Adsorbed Water Films

Chao Gao

D. Kuhlmann-Wilsdorf

D. D. Makel

Department of Materials Science,
University of Virginia,
Charlottesville, VA 22901

Stiction resulting from moisture effects at small elastic contact spots has been identified and studied using bundles of fine, gold-plated copper fibers sliding on a gold-plated copper surface. The relevant measurements were made in the hoop apparatus which permits simultaneous monitoring of the momentary coefficient of friction and electrical contact resistance. Previous studies made with the hoop apparatus have shown that under the action of high local pressure, adsorbed moisture is expelled from between the contact spots leaving only one monomolecular layer of adsorbed water on each of the contacting surfaces. Additional details of the observations are varied and permit a refined analysis. Stiction results during periods of very slow motion or rest through local energy reduction at the spots as excess water is slowly drained in the course of molecular ordering of the two absorbed layers. Complex variations of kinetic friction with humidity and sliding speed are explained through the interplay of excess molecules between the contact spot surfaces, meniscus formation, fluid drag about the spots, and shear thinning in that flow.

Introduction

The tribological and electrical behavior of surface films have recently received a great deal of attention in three areas; 1) the prevention of damage to magnetic head/disk systems caused by stiction (Bhushan and Dugger, 1990; Li et al., 1989; Liu and Mee, 1983), 2) the determination of the effects of surface films on scanning tunneling (STM)/atomic force (AFM) (McClelland and Mate, 1988; Schneir et al., 1988; Mamin et al., 1986) and surface force microscopy (Alsten and Granick, 1988; Homola et al., 1989; Chan and Horn, 1985), and 3) the optimization of sliding conditions for high current density collectors (Johnson, 1986; Adkins and Kuhlmann-Wilsdorf, 1979; 1980).

Both in the laboratory and in daily life, adsorption films on solid surfaces are unavoidable except when the surfaces are carefully cleaned and degassed in ultra high vacuum (Bowden and Throssell, 1951); and on nonreactive surfaces in the normal atmosphere water is the most prevalent adsorbate. For gold-plated surfaces, previous studies (Gao and Kuhlmann-Wilsdorf, 1990a, 1990b, 1991) conducted using the hoop apparatus have revealed that for friction and interfacial electrical resistance the most sensitive experimental variables are humidity and sliding speed, with secondary effects caused by applied load. It was also found that for gold-plated samples and substrates, atmospheres of clean air, argon, nitrogen, carbon dioxide, oxygen and vacuum down to about 0.01 Torr all yield essentially the same results.

The advantage of the present geometry, which employs bundles of gold-plated fibers, is that it renders the constriction resistance negligible due to the large number of the contact spots (Gao and Kuhlmann-Wilsdorf, 1990a; Holm, 1967). In this condition the contact resistance (R) under normal force P becomes

$$R \approx \frac{\sigma_F H}{P} \tag{1}$$

with H the impression hardness of the softer side and P/H equal to the area for stationary plastic contact, which is about the same as for the kinetic contact case provided μ is small (say less than 0.5) (Mcfarlane and Tabor, 1950). Also, the large number of contact spots which results from the use of our metal fiber brushes makes the changes in both number and size of the contact spots statistically insignificant in regard to the interfacial resistance. Furthermore, since the local contact pressures at the constant spots approach or equal the pressure necessary for plastic flow, this results in a somewhat uniform pressure distribution between the contact spots, except in the peripheral regions where the contribution to the contact resistance is *not* dominant.

Throughout these and previous investigations the film resistivity σ_F between contact spots of gold-plated surfaces has been experimentally determined to be near 10^{-12} Ωm^2 within a factor of 2 or so, regardless of the experimental conditions (Adkins and Kuhlmann-Wilsdorf, 1979; 1980; Simmons, 1963). This value of film resistivity is indicative of an electron tunneling film with a thickness of 0.5 ± 0.1 nm between the contact spots (Adkins and Kuhlmann-Wilsdorf, 1979; Gao and Kuhlmann-Wilsdorf, 1990a; Holm, 1967), corresponding to a two monomolecular layer thick water film since, in our tests, water is obviously the most prevalent adsorbate on the clean gold surfaces. Because the film resistivity is extremely sensitive to the separation distance, as clearly described in reference [20], the average number of monomolecular layers at the con-

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GEOMETRICALLY NECESSARY, INCIDENTAL AND SUBGRAIN BOUNDARIES

D. Kuhlmann-Wilsdorf
University of Virginia, Department of Materials Science
Charlottesville, VA 22901
and
Nie' 'Hansei.
Materials Departmen' ɞ National Laboratory
DK-4000 Ro... 'de, Denmark

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Introduction

In the course of polyslip, materials deforming via dislocation motion break up into mutually misoriented volume elements on three levels. The most pervasive and of smallest scale is the "mosaic block structure" formed of mutually misoriented dislocation cells separated by dislocation cell boundaries. On the other end of the scale, already the first published micrographs on slip lines, in the classic paper by Ewing and Rosenhain (1), document the break-up of crystal grains into domains with different operative slip system combinations. These domains are clearly caused by stress variations due to the interference among neighboring grains. Geometrically as well as from other early slip line evidence (1-3) it is apparent that there are typically more than ten but less than one hundred domains per grain, in each of which commonly three to five slip systems operate simultaneously. Likewise it is obvious that interpenetrating glide on different combinations of slip systems, causes lattice rotations which initially increase fast with strain but sooner or later lead to a final orientation depending on the selection of operative systems, e.g. <112> parallel to the tensile axis in double glide of fcc single crystals. As a direct geometrical consequence, boundaries must arise between the different domains. The boundaries are undoubtedly somewhat diffuse initially but presumably sharpen up with strain.

Related pioneering observations document the evolution of those lattice misorientations within grains in the course of straining, partly obtained with the Berg-Barrett method (4,5), partly with direct x-ray reflexes (6-9), and partly through metallography, notably by Wood and co-workers (6,7). All of the studies demonstrated that plastic deformation of polycrystals leads to the break-up of grains into volume elements of mutually misoriented material giving rise to fragmentation of x-ray spots and clearly visible tilts on an initially smooth metallographically polished surface, on a scale much larger than dislocation cells.

An additional form of fragmentation but on an intermediate scale, namely into "cell blocks" (10-13) which are typically much smaller than the domains, has been discovered only recently. This break-up was recognized through the observation of "dense dislocation walls" and "microbands" (11,14) which, on account of their much greater length and associated rotation angles, geometrically must delineate volume elements larger and more strongly misoriented than individual cells. Mathematically such misorientations can be explained only through the operation of different selections of glide systems within the so delineated volume elements, i.e. the cell blocks.

Sharp boundaries across which the combination of slip systems and associated lattice misorientations change, and which may be reasonably identified with cell block boundaries, were indeed observed in early electron microscopical observations of aluminum single crystals (15-17) and also on copper and silver (18), see Fig. 1; but their true nature and origin was not recognized until now. More recent

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Microstructural evolution in rolled aluminium

Bent Bay
The Engineering Academy of Denmark, Department of Mechanical Engineering, Lyngby (Denmark)

Niels Hansen
Materials Department, Risø National Laboratory, Roskilde (Denmark)

D. Kuhlmann-Wilsdorf
University of Virginia, Department of Materials Science, Charlottesville, VA 22901 (USA)

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Abstract

The evolution of the microstructure of cold-rolled pure aluminium (99.996%) was studied by transmission electron microscopy (TEM), extending a previous study that was limited to 30% strain ($\varepsilon = 0.36$). The present work concentrates on rolling strains from 50% ($\varepsilon = 0.69$) to 90% ($\varepsilon = 2.3$). The observations are explained through the governing principle that, in the course of polyslip, grains break up into volume elements within each of which fewer slip systems operate simultaneously than required by the Taylor model. The boundaries between the volume elements accommodate the lattice misorientations arising from the correspondingly different glide. They are therefore geometrically necessary boundaries and in TEM they appear variously as dense dislocation walls, different types of microbands and subgrain boundaries. The morphology and the spatial arrangement of the geometrically necessary boundaries were characterized and it is discussed how these boundaries form with inoreasing strain as an integral part of the microstructural evolution.

1. Introduction

In a recent paper [1] the microstructural evolution during the plastic deformation of polycrystals was analysed in terms of two governing principles: (i) a continuous subdivision of grains into volume elements deforming through different combinations of slip systems and (ii) mutual trapping of dislocations into low energy configurations (LEDS). Good agreement was found between these principles and transmission electron microscopy (TEM) observations for a number of medium or high stacking fault energy materials deformed by different modes to low and medium strains [1–7]. The governing principles should also apply to materials deformed to high strains but experimental observations in the strain range from 0.7 to 2.3 are scarce. This range was covered in the present experiments where the microstructural evolution was analysed in cold-rolled pure aluminium (99.996%) deformed 50%–90% by cold-rolling.

2. Governing principles

In refs. 1 and 3 it was suggested that a governing principle of plastic deformation is that the number and selection of simultaneously acting slip systems differ between neighbouring volume elements and that in every element the number of slip systems is in general smaller than that required by the Taylor model [8] for microscopic strain accommodation.

Fewer slip systems lead to a reduction of dislocation intersections and thus fewer jogs and lower flow stress at the expense of less perfect approximation to homogenous deformation. However, the constraints between the differently oriented grains will, with locally fewer simultaneously operating systems, lead to the corresponding subdivision into volume elements with increasingly different lattice orientations but which collectively closely approximate homogenous strain. The subdivision appears to take place on a smaller and smaller scale beginning with relatively few domains per grain at small strains to many cell blocks and finally to a large number of subgrains as the predominant arrangement at large strains. Each volume element is characterized by its own combination of slip systems, therefore by different lattice rotations with strain, and the dislocation boundaries between the elements arise out of geometrical necessity. It is therefore suggested [9] that such boundaries should be termed geometrically necessary boundaries (GNB) in order to distinguish them from ordinary cell boundaries which are

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USES OF THEORY IN THE DESIGN OF SLIDING ELECTRICAL CONTACTS

Doris Kuhlmann-Wilsdorf
Department of Materials Science, University of Virginia
Charlottesville, VA 22901

ABSTRACT

Ragnar Holm has pioneered the broadly-based use of theory for understanding, and hence improving, electrical contacts. The present paper discusses subsequent such uses in four areas: (i) Studies of monolithic metal-graphite brushes for determining their operating limits. (ii) Development of high-performance metal fiber brushes based on theoretical considerations. (iii) Developing a computer program for calculating contact spot temperatures, being the principal determinant of top brush performance. (iv) Studies of microscopic processes at a-spots including adsorbed layers, with the aim of optimizing the operating conditions of sliding contacts.
Key Words: Metal-graphite, fiber brushes, flash temperature, adsorbed gases.

INTRODUCTION

Background

The association of the present writer's name with that of Ragnar Holm through the 1991 Ragnar Holm Scientific Achievement Award will be a source of permanent satisfaction and pride. Indeed, the impact of Ragnar Holm's towering personality and pioneering work in the field of electrical contacts is almost unique for any important area of science and technology, perhaps comparable only to the similarly dominant influence of Wilhelm Roentgen and his work on the evolution of the science and technology of x-rays at the turn of this century.

In each case, it was the combination of a brilliant mind, rigorous application of scientific principles, uncompromising reliance on theoretical understanding and untiring work, which made the contributions of these men incisive. Therefore, trying to convince the present audience, at a Holm Conference, of the importance of theory in tandem with experimental research for the development of electrical contacts would indeed compare to carrying owls to Athens or coals to Newcastle. This paper will therefore take that shared conviction for granted and will simply seek to illustrate it by means of a few examples which have preoccupied this writer for the past fifteen years or so.

Four principal topics will be discussed. Each of these is connected to the project which brought this writer to do research on electrical contacts, in 1976 on the initiative of the late, admiringly remembered Ed Salkowitz, then head of the materials division of the Office of Naval Research in Arlington. This project was the development of a homopolar motor/generator for Navy use. At the time it was foundering for want of the requisite current collectors (i.e. "brushes"). According to design specifications they should have been able to operate long-term with dimensionless wear of at most 10^{-10} at a speed of 40m/sec and a current density of 2000 Amps/in^2, with a total loss of no more than 0.25 watt per brush per ampere conducted; - specifications which are yet to be achieved, one may add.

Research Goals

Since 1976, Dr. Salkowitz's initiative has led to years of fundamental studies in our laboratory, initially under sole ONR sponsorship and later supplemented by funding from different other agencies, especially DARPA. That research aimed

(i) to investigate the previously best candidate brushes, namely made of silver-graphite (Ag-C) with about 75% silver content by weight, in order to provide a base from which improvements should be made;

(ii) to reveal theoretical lower limits for contact resistances;

(iii) to develop methods for the efficient computation of the "flash temperature", i.e. the local temperature at contact spots, under a very wide range of conditions, since it was suspected from the outset that brush performance is sensitively dependent thereon;

(iv) to more deeply understand the conditions which affect mechanical friction and wear at the lowest possible contact resistance.

Outline of Major Results Obtained

As will be discussed in greater detail later, the most important results obtained so far, in our laboratory within the above four areas, include the following:

(i) Clarification of time-lag effects through temperature induced changes in the surface films of Ag-C brushes (1-3); expansion of the performance limits of such brushes beyond the previously known range (4,5); and demonstration of the mechanism through which moisture facilitates graphite lubrication (6-8).

(ii) The development of metal fiber brushes (9-13) and demonstration that, on account of their small contact spot diameters, these have the theoretically lowest possible contact resistance (11-17) among all moving and/or releasable contacts when covered with one monomolecular layer of adsorbed gas on each side, preferably water vapor (10). The correlated film resistivity in that

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OVERVIEW NO. 96

EVOLUTION OF F.C.C. DEFORMATION STRUCTURES IN POLYSLIP

B. BAY[1], N. HANSEN[2], D. A. HUGHES[3] and D. KUHLMANN-WILSDORF[4]

[1]The Engineering Academy of Denmark, Department of Mechanical Engineering, Lyngby, Denmark, [2]Materials Department, Risø National Laboratory, 4000 Roskilde, Denmark, [3]Materials Department, Sandia National Laboratories, Livermore, CA 94550, U.S.A. and [4]Department of Materials Science, University of Virginia, Charlottesville, VA 22901, U.S.A.

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Abstract—The microstructural evolution during polyslip in f.c.c. metals is investigated by the examples of Al, Ni, Ni–Co alloys and an Al–Mg alloy, deformed at room temperature either by rolling or by torsion. The principles governing this evolution appears to be the following: (a) There are differences in the number and selection of simultaneously acting slip systems among neighboring volume elements of individual grains. In any one volume element (called a cell block), the number of slip systems falls short of that required for homogeneous (Taylor) deformation, but groups of neighboring cell blocks fulfil the Taylor criterion collectively. (b) The dislocations are trapped into low-energy dislocation structures in which neighbor dislocations mutually screen their stresses. The microstructural evolution at small strains progresses by the subdivision of grains into cell blocks delineated by dislocation boundaries. These boundaries accommodate the lattice misorientations, which result from glide on different slip system combinations in neighbouring cell blocks. The cell blocks are subdivided into ordinary cells and both cell blocks and cells shrink with increasing strain. All observations appear to be in good accord with the theoretical interpretation. However, some problems remain to be solved quantitatively.

Résumé—On étudie l'évolution microstructurale pendant le glissement multiple dans les métaux c.f.c., dans des alliages d'Al, de Ni, de Ni–Co et de Al–Mg, déformés à la température ambiante soit par laminage, soit par torsion. Les principes qui gouvernent cette évolution sont les suivants: (a) Il existe des différences dans le nombre et le choix des systèmes de glissements simultanément actifs parmi les éléments de volume entourant les grains individuels. Dans un élément de volume quelconque (appelé bloc cellulaire) le nombre de systèmes de glissement n'atteint pas celui que requiert la déformation homogène (Taylor), mais des groupes de blocs voisins remplissent collectivement le critère de Taylor. (b) Les dislocations sont piégées dans des structures de dislocations de basses énergies dans lesquelles les dislocations voisines constituent mutuellement des écrans de contraintes. L'évolution microstructurale aux faibles déformations consiste en une subdivision des grains en blocs cellulaires délimités par des parois de dislocations. Ces parois accommodent les désorientations du réseau, qui résultent du glissement sur des combinaisons de différents systèmes de glissement au voisinage des blocs cellulaires. Ces blocs sont subdivisés en cellules ordinaires et tant les cellules que les blocs cellulaires retrécissent lorsque la déformation augmente. Toutes les observations semblent en bon accord avec l'interprétation théorique. Cependant, il reste à résoudre quantitativement quelques problèmes.

Zusammenfassung—Die Entwicklung der Mikrostruktur in k.f.z. Metallen während Vielfachgleitung wird an den Beispielen Al, Ni, Ni–Co-Legierungen und einer Al–Mn-Legierung, verformt bei Raumtemperatur durch Walzen oder in Torsion, untersucht. Das dieser Entwicklung unterliegende Prinzip scheint wie folgt zu sein: (a) Es bestehen Unterschiede in Anzahl und Auswahl der gleichzeitig aktivierten Gleitsysteme in benachbarten Volumelementen der einzelnen Körner. In jedem Volumelement (genannt Zellblock) ist die Zahl der Gleitsysteme geringer als die für homogene (Taylor-) Verformung erforderliche, aber Gruppen benachbarter Zellblöcke erfüllen kollektiv das Taylor-Kriterium. (b) Die Versetzungen werden in Konfigurationen niedriger Energie, in denen benachbarte Versetzungen ihre Spannungsfelder gegenseitig abschirmen, eingefangen.

1. INTRODUCTION

The development of deformation microstructures in f.c.c. metals at low homologous temperatures has been studied extensively in single crystals and polycrystals [e.g. Refs 1–14]. For materials with a medium or high stacking fault energy the earliest microstructures develop with strain from "tangled" dislocations to a structure consisting of cells or subgrains. The profuse jogging and kinking at low strains, which gives the visual impression of tangling, is due to dislocation point defect interactions and is not significant except at the lowest stresses [8]. Additionally, especially in polyslip, a number of larger inhomogeneities also characterize the deformed state, for example dense dislocation walls, microbands,

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Department of Materials Science, University of Virginia, Charlottesville[1])

Theory of Worksoftening in High-Performance Alloys

By

DORIS KUHLMANN-WILSDORF and H. G. F. WILSDORF

Dedicated to Professor Dr. PETER HAASEN on the occasion of his 65th birthday

In conventional alloys ductility decreases with rising flow stress to negligible values at some maximum yield stress (τ_m), whereas high-performance alloys, e.g. formed through mechanical alloying or nano-powders, can have much higher yield stresses with ductility, but tend to worksoften. A simple theory is presented, based on the LEDS concept, to account for both of these behaviors: The flow stress is $\tau \approx \tau_0 + \text{const}\sqrt{\varrho}$ with ϱ the dislocation density, and the workhardening coefficient is $\theta \approx d\tau_0/d\gamma + C\beta$ with β the rate of glide dislocation trapping. β depends on the specific LEDS formed but always decreases with stress and can become negative for $\tau > \tau_m$ at artificially high ϱ. Worksoftening results when unconventional manufacturing methods have produced LEDS with metastable ϱ and/or τ_0 values that are higher than conform to the LEDS generated through the conventional straining conditions in testing or use.

In konventionellen Legierungen nimmt die Duktilität mit zunehmender Festigkeit ab, um bei einer oberen Spannung (τ_m) zu verschwinden. Dagegen können wesentlich höhere Streckgrenzen mit nennenswerter Verformbarkeit durch mechanisches Legieren oder Verwendung von Feinstpulvern erzielt werden, aber solche Legierungen neigen zur Erweichung durch Verformung. Beide Erscheinungen können aufgrund des LEDS Konzeptes wie folgt erklärt werden: Die Fließspannung ist $\tau = \tau_0 + \text{const}\sqrt{\varrho}$ (ϱ Versetzungsdichte), und der Verfestigungskoeffizient ist $\theta \approx d\tau_0/d\gamma + C\beta$ (β Rate der Versetzungszunahme), β hängt von der spezifischen LEDS ab, sinkt aber immer mit der Spannung und kann bei überhöhten Versetzungsdichten negativ werden. Erweichung kann deswegen durch metastabile LEDS mit zu hohen τ_0 und/oder ϱ-Werten entstehen, wie sie etwa durch unkonventionelle Herstellungsmethoden erzeugt werden.

1. Introduction

The LEDS (low-energy dislocation structure) concept has proven to be a very fruitful guiding principle for understanding plastic deformation and workhardening [1, 2]. According to it, the dislocation content of crystalline materials approaches that among all configurations accessible to them which most nearly minimizes the free energy per unit length of dislocation line. When dislocations are relatively free to leave their glide planes, they minimize their energy by mutual trapping into dislocation rotation walls [3 to 8]. This is the reason for the widely observed formation of cell structures, typically composed of dislocation rotation walls variously distinguished as (i) ordinary dislocation cell walls, and as (ii) dense dislocation walls (DDW's), and (iii) microbands (MB's) of different types which together delineate cell blocks (CB's), wherein the manifold details depend on the type and severity of the preceding plastic deformation [9 to 12].

The very general correlation of high yield strength and low ductility of conventionally produced alloys, which seemingly puts an upper limit on achievable strength combined

[1]) Charlottesville, VA 22901, USA.

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IMPROVED SLIDING ELECTRICAL BRUSH PERFORMANCE THROUGH THE USE OF WATER LUBRICATION

by

David D. Makel and Doris Kuhlmann-Wilsdorf

University of Virginia
Charlottesville, VA

ABSTRACT

Electrical and wear performance of sliding electrical contacts is critically dependent on the local contact spot temperature resulting from Joule and frictional heating. Continuous operation under significant heat input rates can raise the temperature to the point of severe performance degradation or catastrophic failure. Using a novel method of water application for both lubricating and cooling, greatly decreased wear rates and increases of the useable current densities in continuous operation have been achieved with metal fiber brushes. The method is expected to be similarly effective with other current collecting systems.

KEY WORDS: metal fiber brushes, water lubrication, high current density collectors

BACKGROUND

Incentive for the Present Work

Although the potentially superior properties of metal fiber brushes, in particular low resistance, low noise, and high speed and current density capabilities, have been demonstrated in numerous investigations (1-5), the development of practical metal fiber brushes has proved difficult. Experience in our laboratory has established three particular problems: i) fiber brushes tend to change shape during long term tests, ii) long term wear rates tend to be prohibitively high, and iii) the brushes have little ability to recover from minor perturbations such as temporary overloading or excessive current.

The present investigations have been focussed on producing metal fiber brushes which avoid these problems without sacrificing their beneficial properties. Specifically, our goal has been to produce a current collection system with properties which will be described later, but the technological advances which have resulted from this work are believed to be of great importance to the field of sliding current collectors in general.

Reasons for Developing Metal Fiber Brushes

Metal fiber brushes, which predate the now nearly ubiquitous monolithic graphite based brushes, are, in their simplest form, a bundle of metal fibers held together at one end, with the loose distal fiber ends contacting the moving substrate. Their primary advantages are direct consequences of the large number of contact spots (on the order of 1 to 3 per fiber) which result from the local compliance of the individual fibers. In fact, an approximately 1 cm^2 metal fiber brush can have many thousands of contact spots, as compared to between approximately 1 to 40 contact spots for a comparably sized monolithic graphite based brush (6-12).

In a typical metal fiber brush the increase in the number of contact spots reduces the constriction resistance (R_c) to the point of being negligible (1), and because the brushes consist of continuous metal fibers the resistance of the brush itself, i.e. the body resistance (R_o), is also typically negligible.

This simplifies the well known relationship for total brush resistance (R_b)

$$R_b = R_o + R_f + R_c \qquad \text{eq.1}$$

to

$$R_b = R_f \qquad \text{eq.2}$$

where R_f is the resistance due to film resistivity. By definition, then, the measured resistance is described by

$$R = A\sigma_f \qquad \text{eq.3}$$

where σ_f is the film resistivity and A is the true area of contact. Correspondingly, the power loss due to Joule heating (Q_J) is defined by

$$Q_J = I^2 R_f = I^2 \frac{\sigma_f}{A} \qquad \text{eq.4}$$

with I the current.

The true area of contact (A) for fully plastic contact spots is generally described using the Meyer hardness of the softer of the two contacting materials (H) and the normal load (P) (13)

$$A = \frac{P}{H} \qquad \text{eq.5}$$

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GRAIN BOUNDARY HARDENING, WORKSOFTENING AND LEDS IN MA ALLOYS

H.G.F. Wilsdorf and D. Kuhlmann-Wilsdorf

Department of Materials Science and Engineering
University of Virginia, Charlottesville, VA 22901

ABSTRACT

According to a recent theory of worksoftening based on LEDS (low-energy dislocation structure) considerations, worksoftening in high-performance alloys is due to either reduction of an excess dislocation density or reduction of the τ_o component of the flow stress, at least a part of which is the Hall-Petch stress. The stress-strain curves of mechanically alloyed (MA) and extruded aluminum alloys for very high temperature applications show distinct worksoftening of the type expected from τ_o reduction. Also the roughly linear decrease of the flow stress with temperature suggests that it is dominated by τ_o, and the very small grain size of ≈0.4μm implicates grain boundary hardening. Since the grain size does not change with straining, the worksoftening must thus be due to a decreasing Hall-Petch constant. Surprisingly regular dislocation networks overlaid on the boundaries in deformed specimens, representing rotation angles of a few degrees, suggest that this occurs through the gradual destruction of a continuous coverage of the grain boundaries by an extremely thin layer of nominally insoluble atoms, probably carbon, while the networks accommodate the mutual rotations of grains during straining.

1. WORKSOFTENING THEORY

The simplified general formula for the flow stress, τ, as a function of dislocation density, ρ, is

$$\tau = \tau_o + \tau_G = \tau_o + \alpha G b \sqrt{\rho} \qquad (1)$$

with G and b the shear modulus and Burgers vector, respectively, and α a numerical constant between about 0.2 and 0.6. The "frictional" stress τ_o includes all parts of the flow stress which are independent of dislocation density, and more often than not is small compared to τ. Parts of τ_o may be based on thermally activated processes while the $\alpha G b\sqrt{\rho}$ part is virtually independent of thermal activation even under extreme conditions.

The LEDS theory of workhardening explains eq.1 in accord with all known experimental evidence. According to it, grain boundary hardening is a part of τ_o as is precipitation hardening (Kuhlmann-Wilsdorf 1989) and the theory accounts for the so often observed Hall-Petch relationship, i.e.

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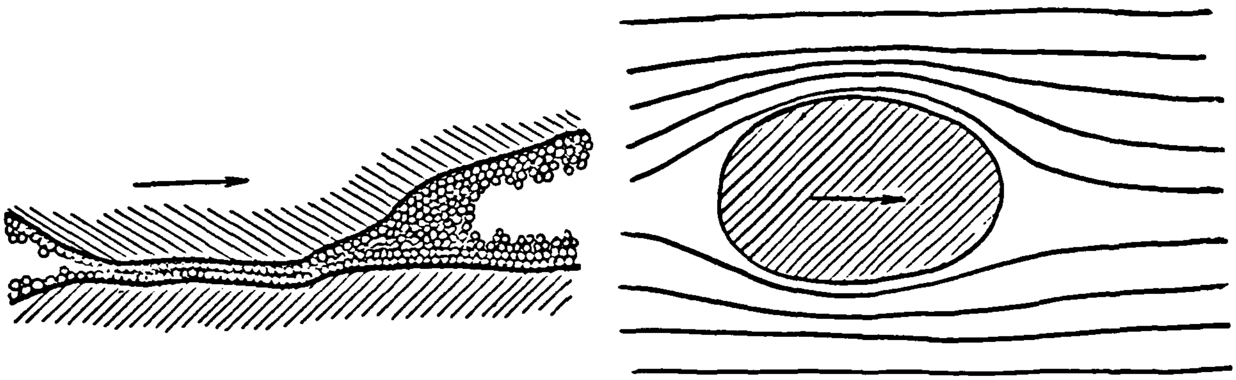


Figure 1. Behavior of adsorbed moisture (and by implication any other adsorbed liquids) at contact spots, depicted in crossection wherein individual molecules are shown as circles at left, and in plan view showing the fluid flow pattern about moving contact spots at right (fig.9 of ref.2)

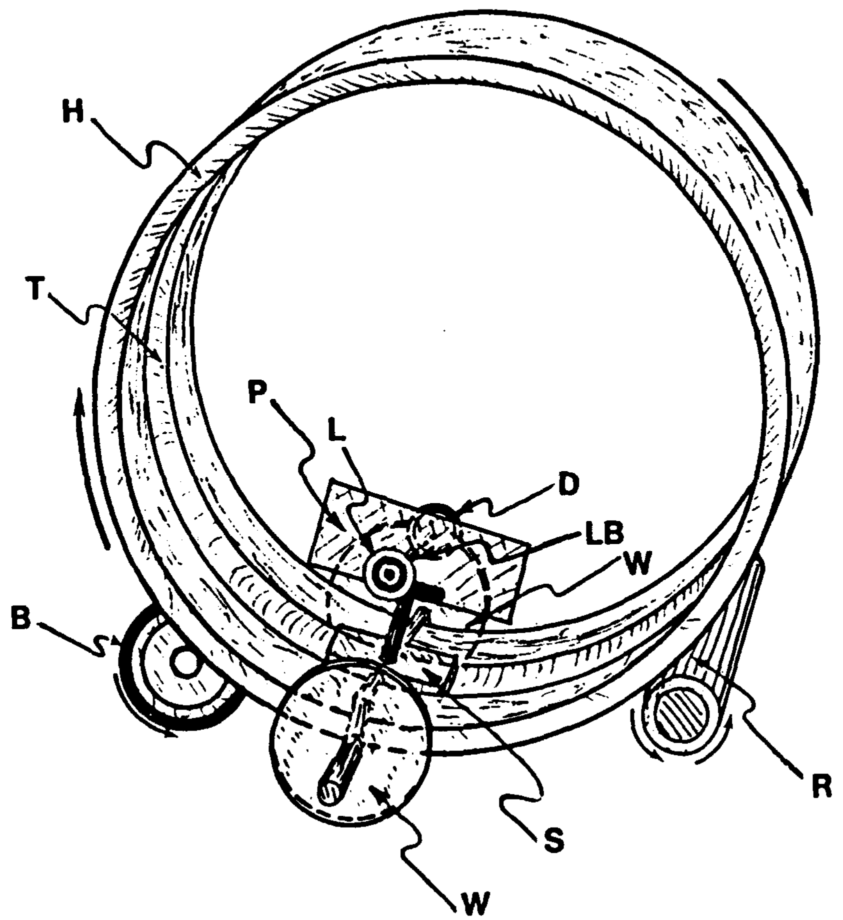


Figure 2. Schematic of the hoop apparatus according to figure 1 of ref. 5

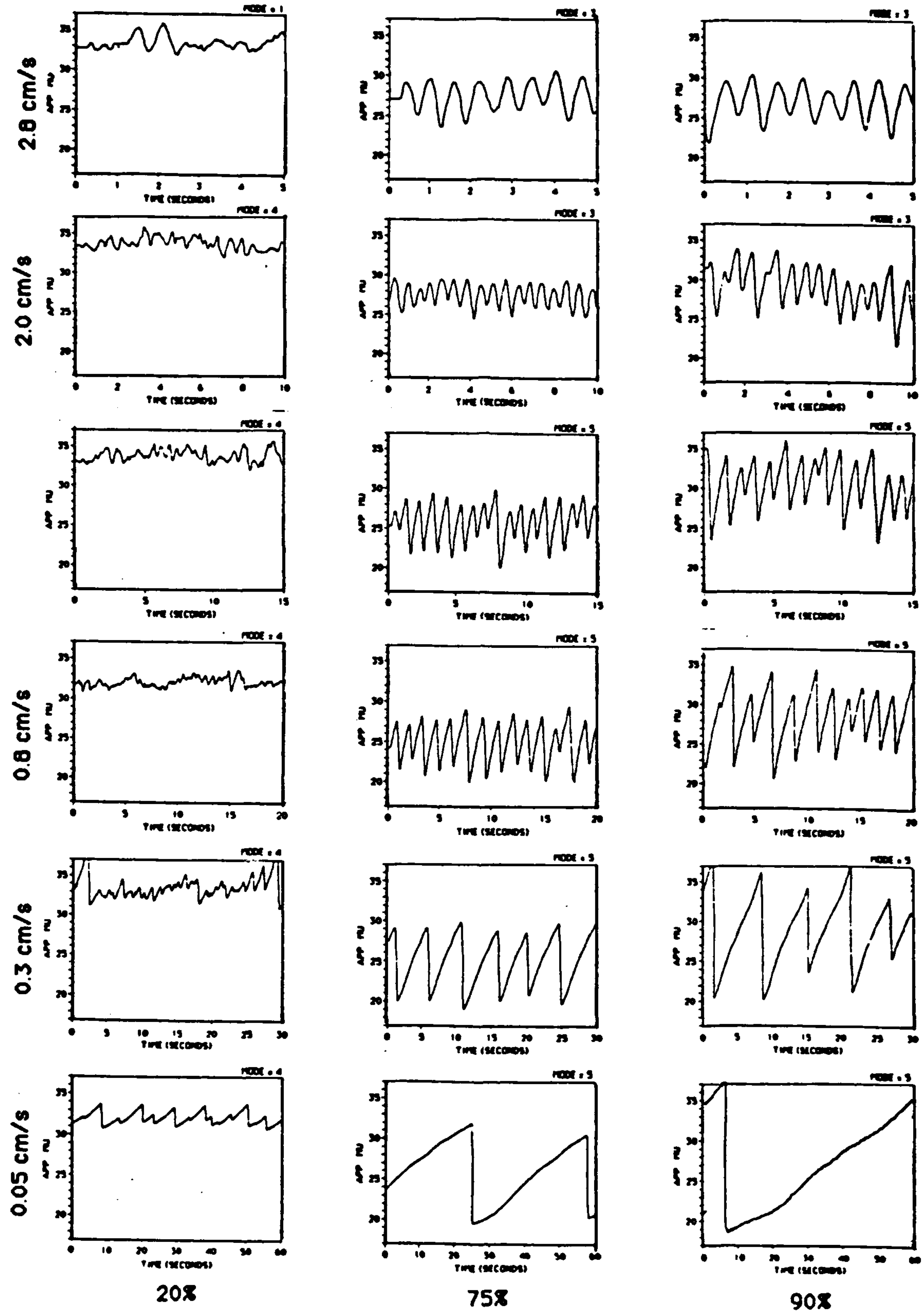
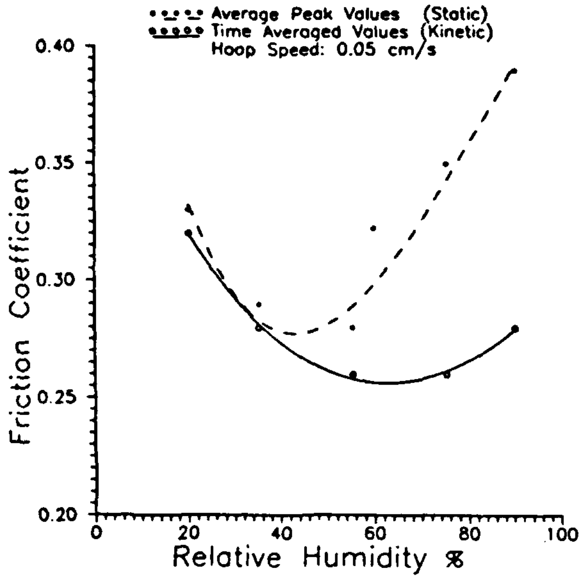


Figure 3. Position-time curves obtained in the hoop apparatus according to ref.7.



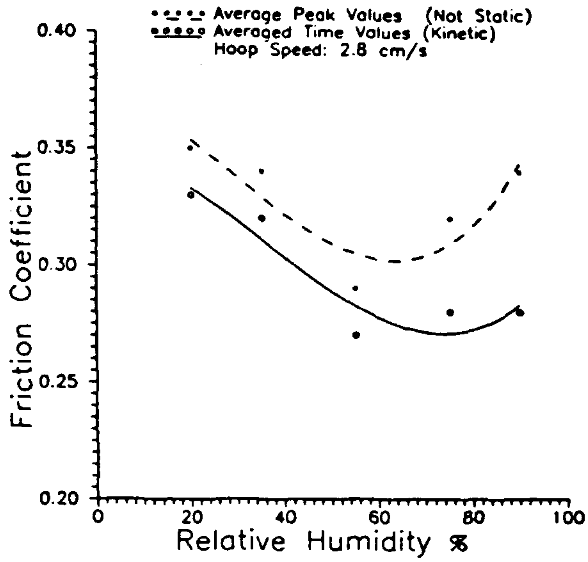
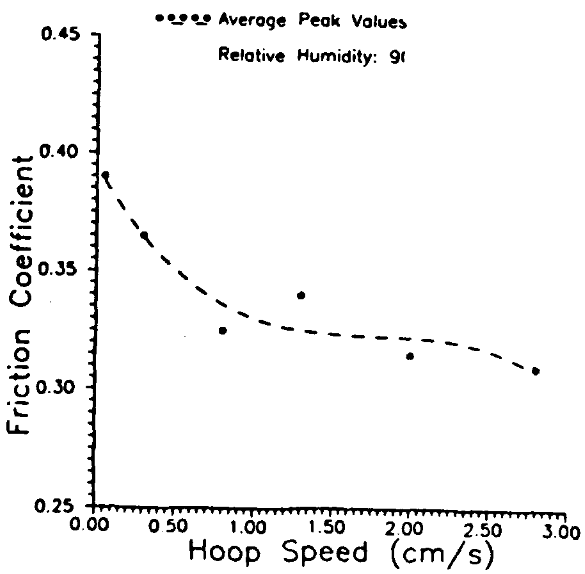


Figure 4. Average peak, i.e. "static" (•), and time-averaged, i.e."kinetic" (O), values of the friction coefficient, during stick-slip at "low" speed (v = 0.05cm/sec) as a function of humidity according to ref. 8.

Figure 5. As figure 4 but for irregular sliding at "high". speed (v=2.8cm/sce) under otherwise same conditions, (ref.8).



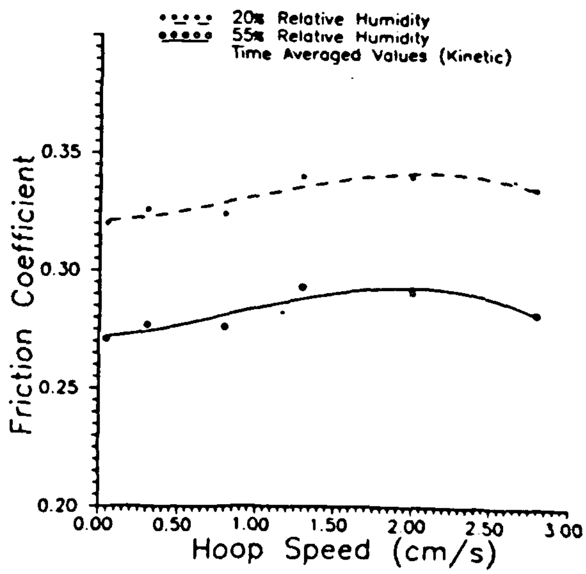


Figure 6. Average peak values (O) of the friction coefficient as a function of velocity for 90% humidity under the conditions of figures 4 and 5. Stick-slip operates for $0 \leq v \leq 1.3$cm/sec.

Figure 7. As figure 6 but for the time-averaged friction coefficient at 20% and 55% humidity.

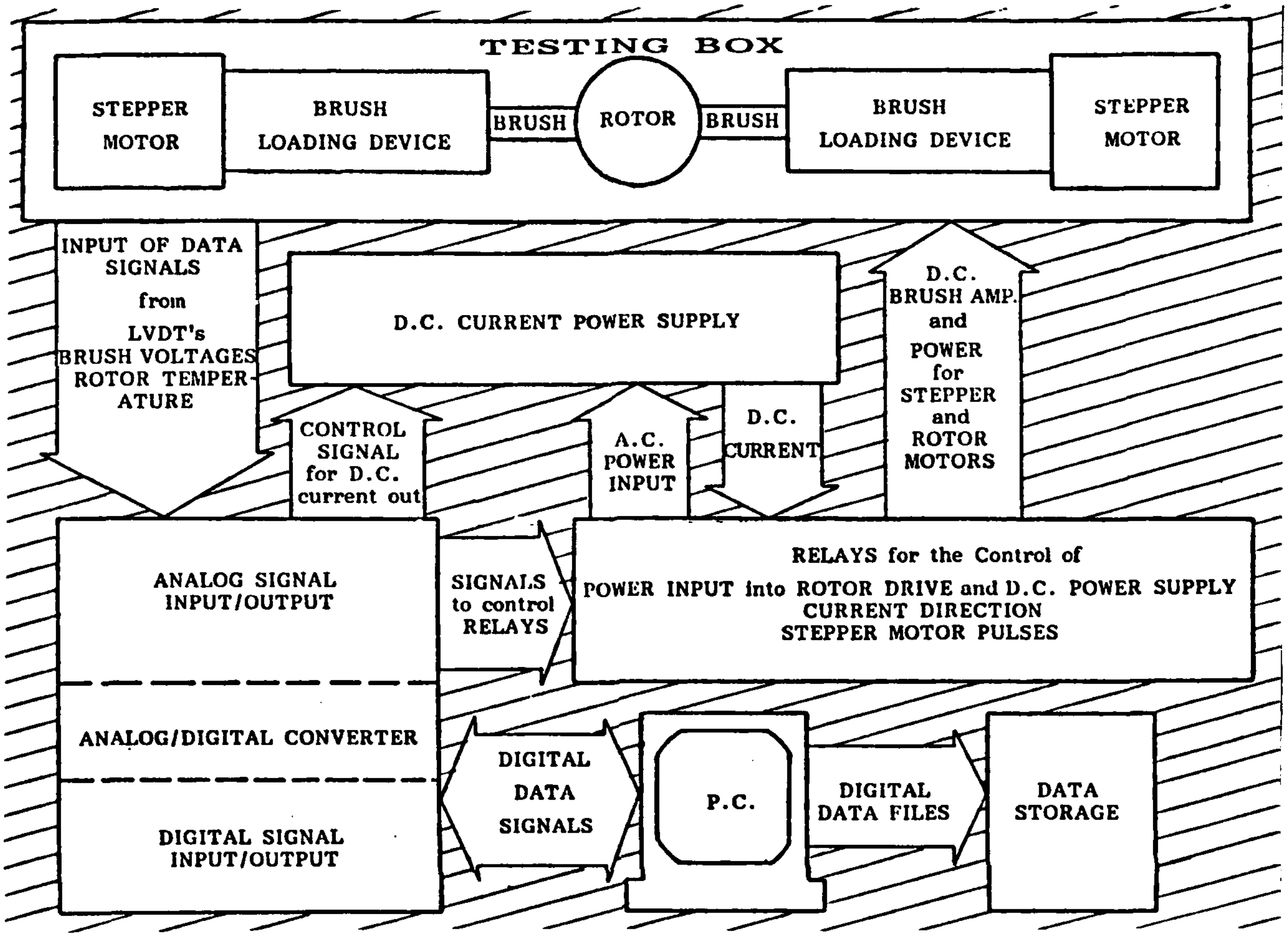


Figure 8. Schematic of the automated brush tester according to figure 1 of ref.25.

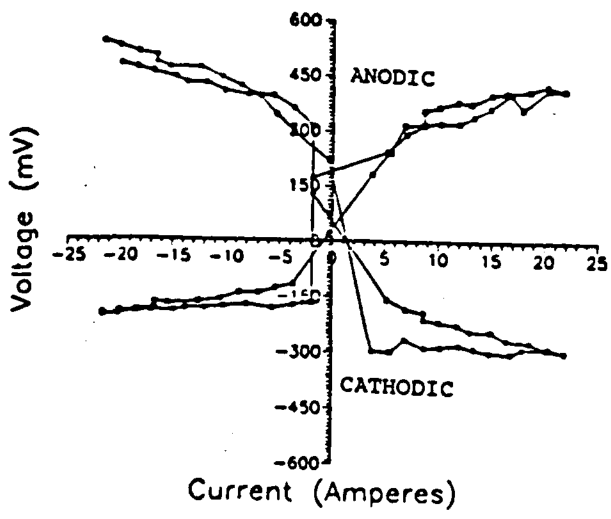


Figure 9. A ramping of current between 23A within ≈1min during a 1200 min test of a pair of copper-graphite brushes running at 10m/sec under a 10A current (ref.25).

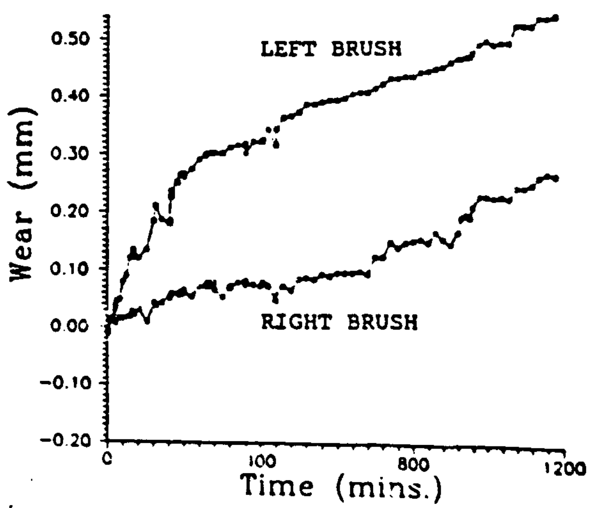


Figure 10 Cumulative wear, i.e. shortening of the brushes, during the same test as Fig.9.

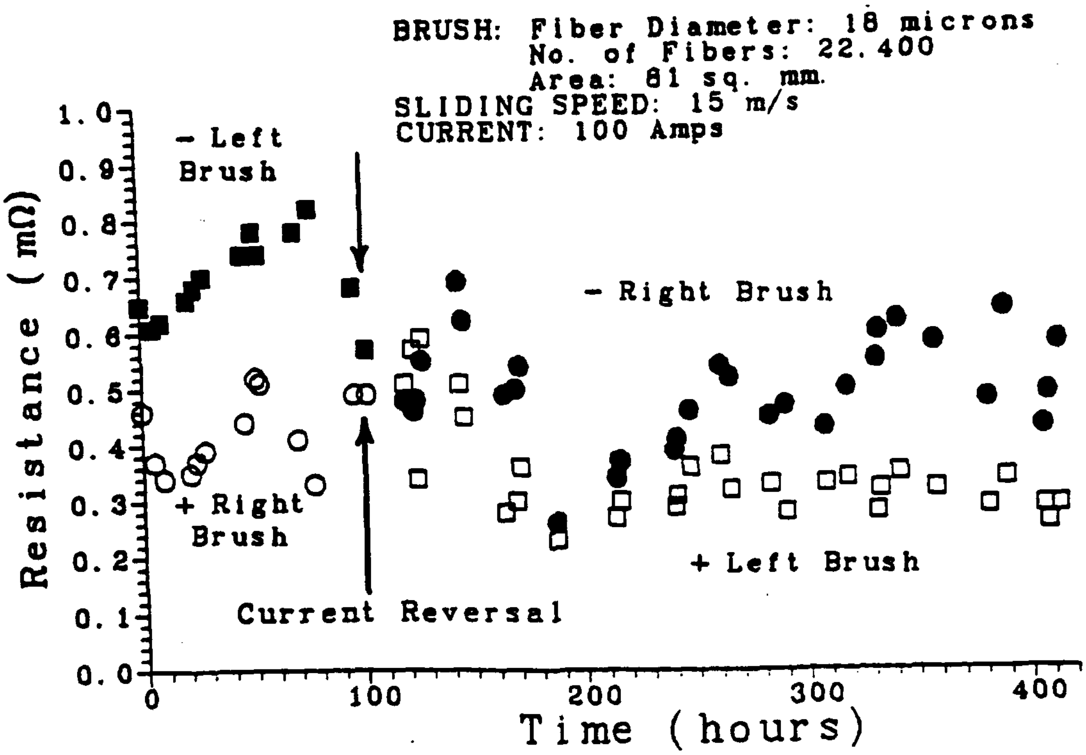


Figure 11. Electrical resistances of left (□,■) and right (○,•) metal fiber brushes, with positive (□,○) and negative (•,■) polarity. Generally, the positive brush has the smaller resistance (ref.26)

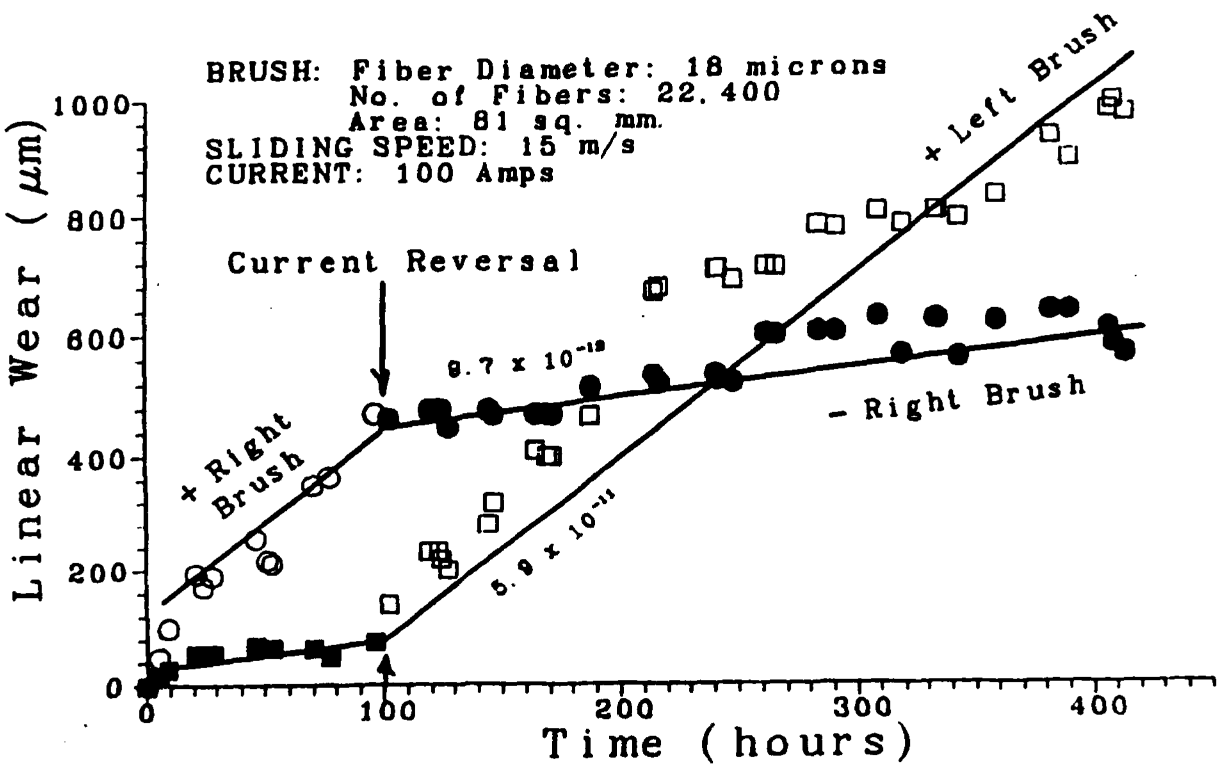


Figure 12. Wear rates observed in conjunction with the the same test as for figure 11.(ref 26). The lower electrical resistance of the positive brush is associated with faster wear.

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